NUCLEAR ENGINEERING VOL. 3 NO. 27 JUNE, 1958

Shippingport—An Appraisal

SHIPPINGPORT power station was due to be dedicated at the end of May, more than five months after its first operation at full power. Although the reasons for the delay are unknown, they certainly do not reflect upon the value, nor the importance of the project, despite the high generating costs (64 mills/kWh) that are quoted in the official report.

Shippingport is claimed to be the world's first nuclear power station designed solely for civilian use, although certain aspects of the design are reminiscent of naval tradition. The whole plant, however, is essentially a prototype or experiment rather than a direct attempt at competitive power, and there is a danger in emphasizing the civilian aspect that the engineering and the cost will be taken as typical of the PWR system rather than typical of a " one-off " job in very special circumstances.

Operationally, the station has so far fulfilled the highest expectations. The run-up to full power from critical was made in a remarkably short space of time (about three weeks) and the reactor portion gave practically no trouble at all. As is inevitable, certain commissioning problems were experienced but these were confined to the conventional sections of the plant. Fuel handling techniques were also not perfect and some modifications were necessary to the element handling tongs but this could hardly be classed as an operational difficulty. To date the reactor has proved stable at all power levels, responding to load changes in the same manner as the Nautilus power unit. Fuel element performance has also been according to design with no failures. At present, the plant is undergoing an extensive series of tests to prove its overall capabilities.

Flexibility

It is perhaps unfortunate that a little more flexibility was not built-in to the reactor so that these tests could be more exacting than is at present possible, particularly in view of the rather dramatic results that are being obtained on the boiling water reactors. It is possible that future designs of large light water-cooled reactors will call for a compromise between the BWR and the PWR systems (this subject will be covered at greater length in a subsequent issue of *Nuclear Engineering*), but it is difficult to see how Shippingport can be used to provide data on partially boiling cores. Nevertheless the plant will add appreciably to the considerable store of information already collected on the PWR and—of equal importance—will develop confidence in the practicability of the system.

Economics

Regarding economics, it must be remembered that a policy of certainty-above-all was adopted (as with Calder Hall) and the generation cost probably bears less resemblance to that possible in a commercial plant than the (undisclosed) cost of power from Calder bears to that from stations now under construction in the United Kingdom.

In its analysis, the A.E.C. has made certain that it cannot be accused of over-optimism. The primary cost, in round figures, was $72m, including the first seed and blanket which is then made equivalent to a capital investment of $68m excluding the core but including $8½m for design engineering. In addition, the power output is quoted at 60 MW whereas the second core at least will generate 100 MW and this is probably not a limiting figure. The generator set alone is quoted at $175/kW (installed capacity) which is high even allowing for poor steam conditions.

Construction by committee, especially a " first-off," must inevitably result in increased costs. Moreover, the rigid time-table must have resulted in the special manufacture of many parts that could have otherwise been practically standard items. To compensate in some degree for this, of course, many components were probably supplied at specially low prices by manufacturers anxious to gain experience in the nuclear field.

The dominant factor, though, was the " better than best " policy which is inescapable in the case of an experimental station. A particularly inconvenient (and therefore expensive) requirement was that of the containment which was spread out over four separate (though interconnected) underground vessels which had to be fabricated and tested before the installation of the reactor and its associated plant. A more compact design, and a more logical construction schedule, would make a significant difference to the capital cost, as would the cumulative effect of many of the special requirements of the smaller components. The main coolant pipes, for example, require a smooth finish inside to resist corrosion and erosion while a smooth finish outside would assist in testing, but the machining of both surfaces to

limits of 125 and 250 micro inches seems extravagant. Instrumentation is another field in which considerable savings could be made if the system were not experimental.

If, in addition to second thoughts on some of these details, the core could be up-rated by a material factor, it is not difficult to believe that the capital cost could be reduced from about \$600/kW to the \$300/kW that is being quoted in the SENN tenders.

Fuel Costs

It is in the fuel cost, however, where the most dramatic change can be made—and must be made if the system is to be competitive even in high-cost areas. The Shippingport analysis shows a figure of 22.7 mills/kWh for capital investment and 38.4 mills/kWh (including 5 mills credit, of which less than 2 mills is for plutonium) for fuel costs. Actual raw material prices are those currently quoted by the A.E.C. and hire charges are based on 4% for the period when the fuel is in the hands of the manufacturer and owner, indicating that some 70% of the initial fuel cost—equivalent to 30 mills/kWh—is for fabrication. It is believed that experience and competition, as well as the development of techniques more suitable to mass-production methods, can bring the element fabrication charges down by at least an order of magnitude. Burn-up can similarly reduce the cost/kWh, the value becoming less important as fabrication costs decrease. Present calculations call for a seed burn-up of 22% and there is every reason to suppose that a future figure of 30-35% is not unreasonable.

It is suggested that if a second station, identical to Shippingport, were built today in the U.S.A., generation costs would be around 35 mills/kWh, but that in a European country with improved techniques, a large PWR station could produce power at something under half this figure. This is still significantly above the 9-mills mark, but it is well on the way. To say the very least, there is now an impressive working demonstration of the PWR in existence at Shippingport. The ultimate economics of the system have still to be proved but there is strong evidence to suggest that in areas where high investment rates obtain, the water-cooled and moderated reactor can directly compete with the Calder type for power stations rated in the 100-200 MW range.

Nuclear Engineering

Scholarship

Nuclear Engineering invites applications for a Post-graduate Scholarship to be awarded for the year 1958-59.

The objects of the Scholarship are to enable the holder:

(a) To pursue studies at post-graduate level directed towards some aspect of nuclear engineering; and

(b) To pursue an approved programme of research in some aspect of nuclear engineering.

The amount of the award will depend upon the circumstances of the successful candidate's case, but will usually be £350 per annum and will in no case exceed £400 per annum. The amount and duration will be assessed by the Selection Committee.

The normal duration of the Scholarship will be one year, or such longer or shorter period as may be approved.

Scholarships will be tenable at universities, technical colleges and other educational establishments (in the United Kingdom) approved by the Selection Committee.

GENERAL CONDITIONS

1. The candidate must be a British subject normally resident in the United Kingdom, with a university degree or its equivalent in engineering, physics, chemistry or metallurgy.
2. A candidate is required to submit a programme of work which he would undertake during the tenure of the Scholarship, together with an estimate of the cost of carrying it out, including personal expenses. Any other awards, allowances, etc., to the candidate, which would be concurrent with the *Nuclear Engineering* Scholarship, should be described.
3. The candidate is to furnish names and addresses of two referees who will be asked to advise the Selection Committee on the qualities of the candidate.
4. The award will be made at the absolute discretion of a Selection Committee.
5. The successful candidate shall devote his whole time to the programme of work proposed by him, with such alterations as the Selection Committee may, with the candidate's agreement, approve at the time of the award.
6. At the completion of a Scholarship, a report is to be submitted, but interim reports on the work may be required from time to time.
7. Application forms can be obtained from the Editor, *Nuclear Engineering*; when completed they should be returned to arrive not later than July 30, 1958.
8. Applications received will be considered by the Selection Committee, and a short list (if necessary) prepared of candidates required for interview by the Committee in London. Approved travelling and subsistence expenses will be defrayed.
9. The Selection Committee reserves the right to elect such candidates as it may approve and the grounds on which particular candidates have been elected or rejected need not be given.
10. In the case of an award for one year, payments will be made as follows:
    October 1—one-half of award;
    January 1—one-quarter;
    April 1—one-quarter.
11. The Selection Committee may terminate a Scholarship at any time if it is not satisfied with the progress or conduct of the student.
12. Candidates should furnish evidence when required to the Committee that their programmes of work have the approval of the head of the institution or department in which they propose to work.

Commentary

The Vienna Agency

The Board of Governors of the International Atomic Energy Agency has now completed four series of meetings in Vienna, and the second General Conference will be held in September of this year.

During its formation and early days there was a real danger that, by becoming yet another political battleground, it would be unable to carry out its tasks effectively. The difficulties in the way of smooth running at the political level are manifold. In the first place there was, as everyone expected, a certain amount of jockeying for position between the United States and the U.S.S.R., particularly over the appointment of the Director General. Happily this trouble appears to have been overcome—at least for the time being.

In addition, the great disparity in technological knowledge, nuclear material production capacity and trained manpower between the few great powers and the rest of the members makes it almost impossible to avoid subconsciously dividing them into the "haves" and "have-nots" with all the internal stresses which such a division implies. The situation is further complicated by the lack of distinction between the prestige value and the real economic gain attached to having an atomic energy programme. The confusion existing in the United States in this matter does not exactly give a lead to countries seeking guidance.

It is still not clear whether successful working arrangements can be made to ensure the economic, safe and equitable distribution of fissionable and other materials. It will, for example, be necessary to ensure that a country wishing to obtain uranium can do so at least as advantageously through the Agency as through a bi-lateral agreement with, say, the United States. Since, of the fissile materials so far offered to the Agency, over 90% comes from the United States, and will presumably be subject to the same conditions of use whether obtained through the Agency or directly, the difficulty is a real one. A country must either be prepared to pay the extra handling charges involved for the advantage, if any, of dealing through the Agency, or to subsidize fuel obtained through the Agency by other states. To date no fuel has been requested, although after the recent meeting of the Board of Governors it was made known that some requests may arise towards the end of the year.

In spite of these difficulties the Agency is giving immediate attention to nuclear training and to schemes which may be expected to raise the standard of living in the less-developed countries. In this field it might well make a major contribution to the peaceful uses of atomic energy, and its success in carrying out this work will depend largely upon its ability to establish a reputation as an independent adviser and effective helper. Its present budget seems inadequate to carry out this task. Moreover, although the great powers have made the major contribution to its budget, the Agency still has to look to these same powers for gifts in kind, and this is not an ideal circumstance to achieve the necessary independence. The recent generous United States offer to provide, free of cost, expert advisers is a case in point.

Many states have, rightly or wrongly, looked with suspicion at offers of help and advice in nuclear matters—especially when the advice given on purely economic grounds conflicts with national aspirations. It will be to the advantage of all concerned if this suspicion can be replaced by confidence. The Agency offers perhaps the only opportunity to do this, and deserves a more vigorous backing with greater direct financial assistance. It, for its part, should continue to fight for its complete independence.

Practical Engineers

Few will disagree with the conclusions reached by the Committee on Practical Training, appointed by the Institution of Mechanical Engineers, that some practical training is essential for all mechanical engineers and that part of it should be planned, and under proper supervision. By "practical training" is meant, of course, training in the processes of the workshop—manual, organizational and human. To omit formal instruction in this would be as lacking in sense as the omission of instruction in mechanical drawing; both are concerned with the language of the profession by which ideas are communicated between different levels and ultimately put into concrete form.

It is a healthy sign that so much attention should now be given to this matter. To some extent it represents a counter-revolution. The gross inadequacies of so much that has passed and continues to pass as practical training have led many engineers to ask whether this phase of a mechanical engineer's education did not do more harm than good; at an impressionable age he might well have his enthusiasm damped and his ideas distorted by association with work and men chosen for convenience rather than for educational worth. The present trend recognizes the bad in the old method by insisting on properly planned and managed training.

It is impossible to generalize; the really good man will rise to the top irrespective of his training. He may even, like Whitworth, derive inspiration from early recognition of inefficient workshop methods. But for the average engineer it is essential to present him only with the efficient in the training stage.

Whatever is eventually done, nothing must be allowed to interfere with the wide-ranging interests of the best type of engineer in this country. Possibly, because his sphere of activity is harder to define than those of other professions, he has, from his university or technical college courses onwards, had a wider range of subjects in his training and experience.

He is frequently to be found in the early development of radically new fields. The contribution of engineers to the development of nuclear energy in this country has been unusually large, and it so happens that men trained as mechanical engineers have played a leading part.

Our future progress in this, as in other fields, depends upon our producing engineers able to work alongside physicists, chemists, and metallurgists, at a very early stage

of development. This calls for a sound training in the scientific fundamentals of engineering as well as the know-how and judgment borne of experience.

We could wish that the Institution could now turn its attention to the wider aspects of engineering education and possibly do something to remove some of the ruts which have appeared in the academic courses. The academics, more than any others, have pointed out the deficiences of " practical training " in the past, although industrialists have not been slow to retaliate in kind. It is, perhaps, time for academic training to undergo an examination as searching as the one just accorded to the practical side.

Plutonium Production

The Science Correspondent of *The Times* recently pointed out that France had broken one of the unwritten rules of atomic energy by publishing her production figures for plutonium. She in fact stated this fairly unequivocably in July of last year when the Marcoule site was thrown open to the Press for the first time. Although production figures for the United Kingdom have not been officially published there is very little doubt as to the present magnitude. With the Windscale reactors out of action, plutonium production is confined to Calder Hall where ratings of reactors have been specified and where the conversion factor can be estimated to within, at any rate, 10% with a fair degree of certainty. This plutonium is, however, earmarked for military purposes and, apart from the militarists, the exact figure is of only academic interest. What is more to the point is the production of enriched uranium and when and how much of this uranium will be made available for small power reactor development. By now a number of companies, on their own or in association with U.S. companies, are actively interested in the small power reactor field for which enriched material is necessary. A Government statement outlining the availability of U^{235} for peaceful purposes would greatly assist these companies in estimating what rates of development they should plan for. In addition confidence would be given to prospective users who also require to plan many years ahead to accommodate what is probably a fair-sized unit of power within their system. Fuel experts are continually reiterating the increasing strain on our fossil resources and emphasizing what a small contribution even a large electricity generating programme can make. It may well be that low pressure steam generation by nuclear reactors will ultimately prove to be of much greater importance than electricity generation. The vital aspect of this is that many years will probably elapse between U^{235} being made available and reactors for process steam becoming a commercial proposition. Even a rough estimate of probable availability would be of considerable assistance to commercial organizations, but one understands that both the Government and the A.E.A. maintain a strictly disinterested attitude towards inquiries on this topic.

Ship Propulsion

The mounting tonnage of ships laid up, not only in the United Kingdom but all over the world further emphasizes the necessity for embarking on a nuclear ship propulsion only when real economic use can be foreseen. The original conception of installing nuclear reactors in very large merchant ships has largely given place to a more realistic appreciation of the shipping industry's demands. The economics of running merchant ships is a highly complex subject, but clearly no operating company can afford to invest vast sums in one very large ship and, until nuclear propulsion offers scope for exploitation in ships of 50,000 tons or smaller, a building project will have little value. There seems little doubt that nuclear propulsive systems, which will find a place in merchant fleets, will be developed in the course of time and a traditionally maritime nation like the United Kingdom naturally wishes to be in the forefront of developments. At present, in this country, no cohesive organization exists to undertake such developments but there is a reasonable probability that the competing interests will have resolved themselves before a reactor system can be chosen which merits a ship-building programme. Nevertheless, there should be no delay in the establishment of international law to cover the operation of such vessels for, even with good will on all sides, formulation of these laws will inevitably be a lengthy process.

U.S. Sales Estimates

U.S. manufacturers can look forward to an estimated $4,000M sales of equipment and components for U.S. and foreign nuclear reactors according to a report prepared by The Atomic Industrial Forum. The nuclear industry anticipates the installation of more than 500 MW(E) nuclear power station capacity in the U.S. by 1960, and the most optimistic assumptions result in competitive prices for nuclear plant by 1964. Anticipated rate of growth would show a U.S. power reactor capacity by 1968 of 6,000 MW(E), but taking pessimistic assumptions, an economic plant would not appear until after 1968 and a capacity of only 2,000 MW(E) would be built by that year.

Expenditures for support of civilian power reactor development on the basis of present commitments are expected to total $150-180M annually until 1960 to 1961. Of this total $90-100M is expected to be contributed by the U.S. Government, $50-60M by private utility firms and $10-20M by manufacturers of reactors and components.

During the past two years, cost estimates have increased sharply but the report predicts reductions in costs for the 1958-1968 period ranging from 15% to 35%. The composite mean capital cost of the large nuclear power plants that will start operations in 1960 is estimated at $430/kW(E), including indirect costs with interest during construction. Cost estimates for similar plants to start operations in 1968 are in the range $360-280/kW(E).

Shortage of Electronic Engineers

The nuclear programme in Scotland is already emphasizing the scarcity of skilled instrumental technicians, already serious in view of the wider use of automation and instrumentation in industry. Major-General Joslin, works manager at Dounreay, at the annual dinner of the Scottish Centre of British Institute of Radio-Engineers, stated that they had some 3,500 instruments in use at Dounreay and were facing an acute shortage of technical staff. The solution adopted had been the training of suitable electrical staff in the details of instrumentation, to allow them the necessary finesse to handle this work. J. S. Pickles, chairman of the S.S.E.B., also referred to the problem when he said that they would have at Hunterston, in due course, a vast number of instruments to service. They were seeking to meet this problem by training their engineers ahead of opening but even this would not meet the needs which were indicated. G. A. Marriot, President of the Institute, stressed the need for Government support in the training of electronic engineers if Britain were to maintain its lead in this field. America undoubtedly subsidized its electronic industry by providing special facilities for scientific training and although this country led in original ideas it was second to the U.S.A. in their application.

SHIPPINGPORT, the world's first large-scale pressurized-water plant, went critical on December 2, 1957, which was, appropriately enough, the 15th anniversary of the world's first chain reaction when Enrico Fermi achieved criticality with a graphite pile under the sports stadium of the University of Chicago. Its full designed output was reached on December 23, less than three years after construction commenced.

The project was carried out under the supervision of Rear-Admiral Hyman G. Rickover, Chief of the Naval Reactors Branch, Division of Reactor Development, U.S. Atomic Energy Commission.

Shippingport was a joint venture between the U.S.A.E.C. and Duquesne Light Co. of Pittsburgh, Pa., the A.E.C. employing Westinghouse Atomic Power Division as principal purchase contractor for the nuclear section while Duquesne assumed responsibility for the electrical generating facilities, and will own them under an agreement reached with the Atomic Energy Commission in 1954. The Duquesne Light Company also own the turbo-generator portion of the plant and are responsible to the A.E.C. for supervision, operation and maintenance of the nuclear portion of the plant. The station, which has cost more than $120M., is located on a 400-acre site on the Ohio River, in Western Pennsylvania, about 25 miles from Pittsburgh.

Table 1.—General Design

Rating, thermal	231 MW 790 × 10⁶ BTU/h
Rating, electrical (gross)	68 MW
Rating, electrical (net)	60 MW
Capacity of turbine	100 MW
Core, 32 seed assemblies in hollow square at 6 in. lattice. Total U^{235}	165 lb
113 blanket assemblies Nat. U in pelletized oxide form	14.6 tons
Safety and control rods	32
Pressure vessel, height	32 ft 6 in.
Diameter	10 ft 6 in.
Operating pressure	2,000 p.s.i.a.
Design pressure	2,500 p.s.i.a.
Thickness	8½ in.
Total coolant flow	22.7 × 10⁶ lb/h
Inlet coolant temperature	507°F
Average coolant temperature	523°F
Outlet coolant temperature	538°F
Seed coolant flow	7.6 × 10⁶ lb/h
Seed coolant velocity	19.9 ft/sec
Seed heat transfer coefficient	9,060 BTU/h-ft²-°F
Seed average heat flux	98,400 BTU/h-ft²
Seed maximum heat flux	418,000 BTU/h-ft²
Blanket coolant flow	13.8 × 10⁶ lb/h
Blanket coolant velocity (lowest orifice region)	4.57 ft/sec
Blanket coolant velocity (highest orifice region)	12.8 ft/sec
Blanket heat transfer coefficient	5,890 BTU/h-ft²-°F
Blanket average heat flux	54,300 BTU/h-ft²
Blanket maximum heat flux	343,000 BTU/h-ft²

General Outline of Scheme

Shippingport consists of a pressurized-water reactor with a heat output of 231 MW (790 × 10^6 BTU/h) operating at 2,000 p.s.i., and generating steam by four coolant loops, only three of which are necessary for full-load operation.

This arrangement not only gives a standby plant, it eliminated a number of manufacturing problems that would

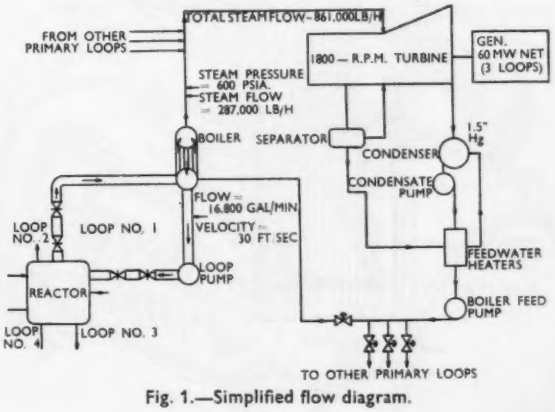


Fig. 1.—Simplified flow diagram.

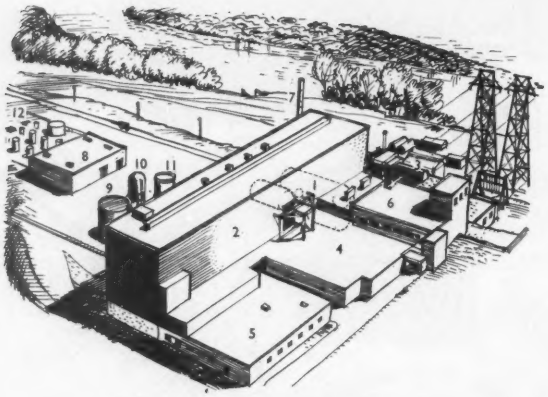


Fig. 2.—General arrangement of station.
1. Reactor. 2. Fuel handling building. 3. Turbine. 4. Auxiliary equipment. 5. Laboratories. 6. Control room and administration. 7. Air treatment stack. 8. Waste disposal. 9. Fuel canal water storage. 10. Primary system water tank. 11. Condensate tank. 12. Decay tank.

have arisen had one single loop been used, since it would have necessitated pumps, valves and pressure parts considerably larger than anything that had ever been built before—even the 4-loop design necessitated piping of the maximum size that manufacturers were prepared to fabricate, and pumps four times larger than any of similar type previously built.

During the design stages, it was decided that control should be based on constant average coolant temperature, rather than on constant steam pressure, principally on account of simpler reactor control, considered of paramount importance in an experimental plant. This decision also took the maximum advantage of the PWR's inherent negative temperature coefficient. It involved, on the other hand, an increase in steam plant costs, due to the variation in steam pressure from 834 to 600 p.s.i.a., between no load and full load.

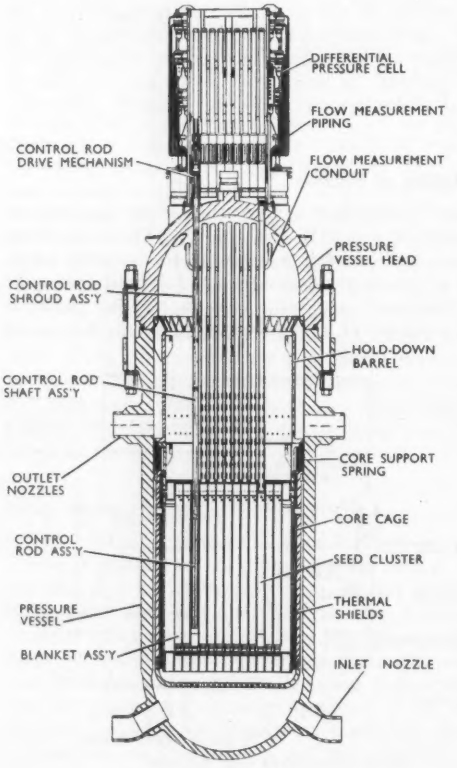
Other design concepts included the complete enclosure and hermetic sealing of all systems containing primary coolant, and the extensive use of corrosion-resistant materials.

Plant Enclosure

The entire plant is enclosed in four steel containers, concrete shielded, and partly below ground level. The reactor itself is housed in a spherical shell 38 ft in diameter with an 18-ft cylindrical dome on top. The two containers for heat exchangers are each 50 ft diameter and 97 ft long, with hemispherical ends, and the auxiliary container is also 50 ft diameter, but is 147 ft long. All the containers are 1 in. thick. All containers are interconnected with ducts 8-12 ft diameter. Air conditioning is provided to keep the temperature to a maximum of 122°F, and the exhaust air is filtered.

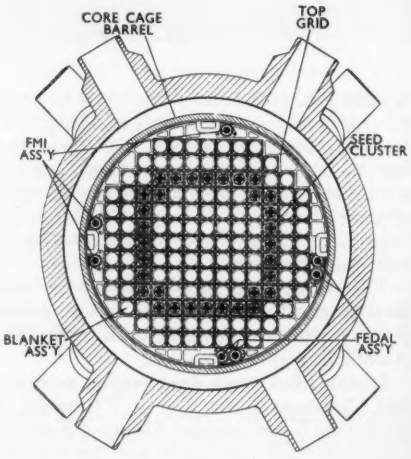
The containment system is designed to handle the release of energy in 20,000 gal of primary coolant water and the energy of the worst conceivable chemical reaction between zirconium and water.

Shielding is in general not less than 5 ft of concrete. The reactor sphere is surrounded by an annular tank of concrete containing a 3-ft thick layer of water to act as a neutron shield.



(Left) Fig. 3.—Section through reactor.

(Right) Fig. 4.—Sectional plan of core.



Pressure Vessel

The main pressure vessel, shown in section in Fig. 3, is some 32 ft 6 in. long overall and 10 ft 6 in. outside diameter, over the walls. Designed for an operating pressure of 2,000 p.s.i.a. and a design pressure of 2,500 p.s.i.a. it has walls 8¼ in. thick, and is fabricated from carbon steel (A.S.T.M. A302 grade B) with a ¼-in. stainless-steel cladding. Four inlet nozzles at the bottom of the vessel and four outlet nozzles at about the middle, feed the coolant loops.

Between the core barrel and the vessel walls are two concentric thermal shields of stainless steel, the outer carrying a stainless steel baffle, or flow guide, to ensure that a part of the coolant passes through the annular space and cools the thermal shields.

The inlet and outlet nozzles are forged carbon steel, clad on the inner face with stainless steel and built up by weld deposition to allow a carbon-carbon steel weld at the vessel wall and a predominantly stainless weld for the pipe stub.

The weight of the reactor vessel is transmitted through

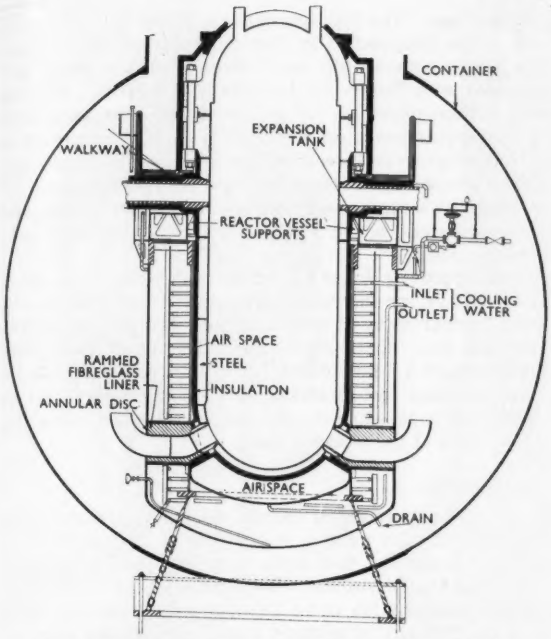


Fig. 5.—Section of reactor containment sphere showing method of supporting vessel and neutron shield.

peripheral lugs to the neutron shield tank. This, constructed from carbon steel, serves the dual purpose of neutron shielding and support for the reactor vessel, and is itself supported by a truncated cone direct from a 5 ft concrete raft, being held by 48 bolts. This cone also supports the spherical containment vessel, as shown in Fig. 5.

The shield tank was built up with the reactor vessel already in position, slung from two 36-in. I-beams laid across the concrete shield, to prevent fouling of the inlet and outlet stubs which had been factory-assembled to avoid the necessity of welding transition joints on site.

A sectional view of the reactor is given in Fig. 3, and a cross-section, or plan, view of the core is shown in Fig. 4.

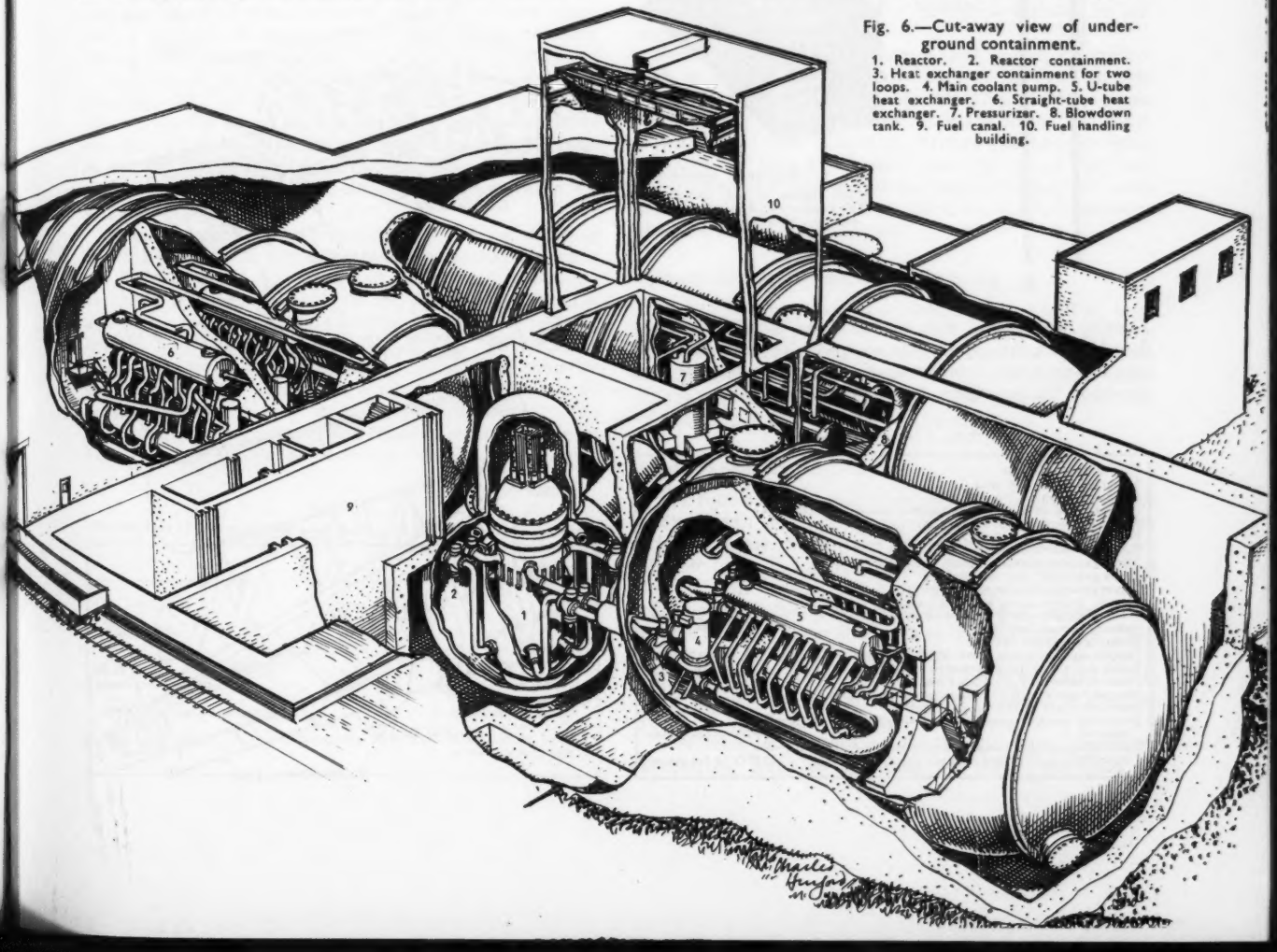
Core

The core is of the two-region or "seed and blanket" type, in which a number of highly enriched seed elements are surrounded with a larger number of natural uranium elements. It is estimated that 50% of the power is derived from fission in the blanket area; this figure approaching 60% at the end of the seed life. The design provides for a first seed life of 3,000 hours at full load.

Referring to Fig. 4, it will be seen that the seed elements, of which there are 32, are disposed in hollow square formation at 6 in. pitch, and the 113 blanket elements are situated inside and outside, the disposition of all the 145 elements being in rows of 7-9-11-(13×7)-11-9-7. The advantage of this type of core is that it permits extensive use of natural uranium, reduces the area that must be controlled (and hence the number of control rods) and has a large negative temperature coefficient of reactivity.

Seed Elements. The actual element itself has a total length of about 110 in., the active fuel portion being about 70 in. long. As can be seen from Fig. 7 each element is made up of a number of narrow plates welded together in groups of 15, four groups being then assembled into a 5½-in. unit with a cruciform space 3¼ in. across tips for

Fig. 6.—Cut-away view of underground containment.
1. Reactor. 2. Reactor containment. 3. Heat exchanger containment for two loops. 4. Main coolant pump. 5. U-tube heat exchanger. 6. Straight-tube heat exchanger. 7. Pressurizer. 8. Blowdown tank. 9. Fuel canal. 10. Fuel handling building.



the control rod. Each of the plates is approximately 2 in. wide and consists of a uranium-zirconium alloy strip 0.039 in. thick, clad in Zircaloy-2 to a total thickness of 0.069 in.

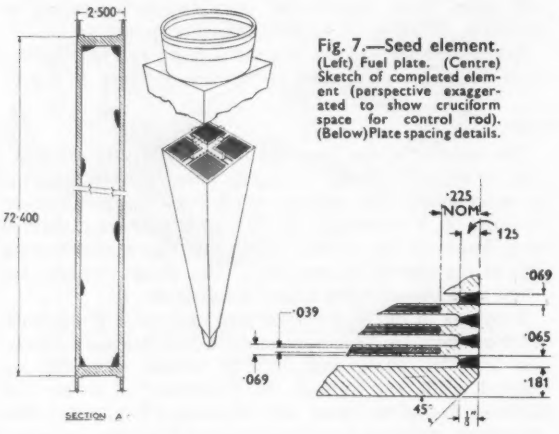


Fig. 7.—Seed element. (Left) Fuel plate. (Centre) Sketch of completed element (perspective exaggerated to show cruciform space for control rod). (Below) Plate spacing details.

Blanket Elements. The fuel in the blanket elements is uranium dioxide pelletized in cylindrical form, contained in tubes of Zircaloy-2 10 in. long and 13/32 in. in diameter, the tubes being assembled in square bundles of 120 between

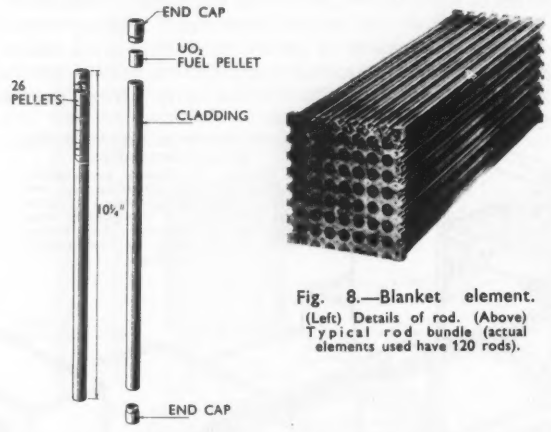


Fig. 8.—Blanket element. (Left) Details of rod. (Above) Typical rod bundle (actual elements used have 120 rods).

Zircaloy end plates with spaced holes to allow coolant flow between the tubes. The complete fuel assembly consists of seven such bundles stacked upon one another with provision for an eighth bundle if required.

Table 2.—Coolant Loops

Total number of loops	4
Steam generators per loop	1
Pumps per loop	1
Number of loops operating at designed power of 60,000 kW	3
Flow per loop at design power	7.59×10^6 lb/h
Pump total developed head	116 p.s.i.
Reactor pressure drop	40.5 p.s.i.
Steam generator pressure drop	43.6 p.s.i.
Steam generator inlet temperature	538°F
Steam generator outlet temperature	508°F
Primary coolant piping outside diameter	18 in.
Primary coolant piping inside diameter	15 in.
Velocity in main loop piping	34.8 ft/sec
Steam generator design:	
Steam output at design power of 60 MW total	860,000 lb/h
Steam side piping design pressure	1,050 p.s.i.g.
Steam pressure at full load at steam generator	600 p.s.i.a.
Normal reactor coolant system operating pressure	2,000 p.s.i.a.
Reactor coolant system design pressure	2,500 p.s.i.g.
Generated electric power range (with automatic reactivity control)	10 MW to full power
Generating electric power range (automatic control of the throttle by system load dispatching)	20 MW to full power

Core Cage. The fuel assemblies are held in a cylindrical unit 155 in. long and 95 in. diameter made entirely of stainless steel, carrying top and bottom support plates and provided with flanges for location and support. The top and bottom plates are of grid or lattice formation with 5¼ in. square boxes on 6 in. centres. The bottom plate carries adaptors to receive the bottom end of the fuel unit and to channel the coolant through it. The fuel units are arranged with compression springs in their lower ends, and locking devices at the top, to ensure that they are held firmly in place.

The supporting flange on the top end of the core cage is supported by the thermal shield inside the pressure vessel, via a circular array of helical springs. To ensure that the core does not "float" on the upward thrust of the coolant flow, there is a "hold-down" barrel approximately 88 in. long, the lower end of which bears against the top surface of the core cage, while the top end bears against a shoulder on the head of the pressure vessel.

Coolant Flow

The flow pattern of the coolant through the reactor, after entering the inlet nozzles is designed so that about 85% passes through the flow guide, into the plenum chamber below the fuel assemblies. The remaining 15% first flows upward between the outer thermal shield and the vessel wall at a velocity of about 5 ft/sec, then divides into two parts and turns downward, one moving in the annular space

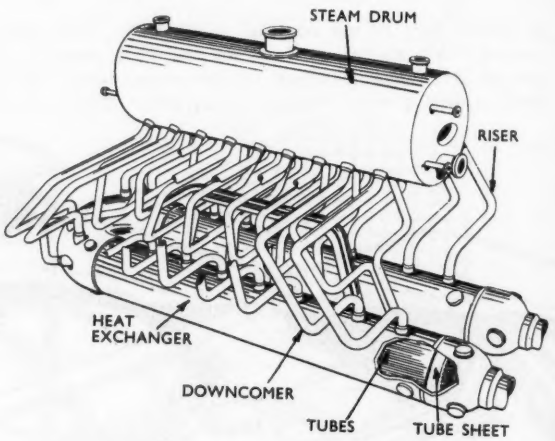
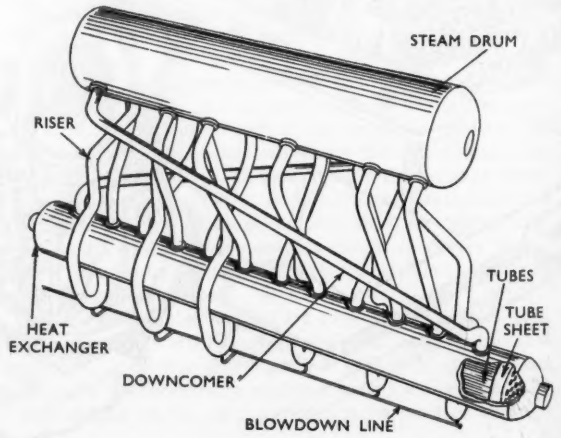
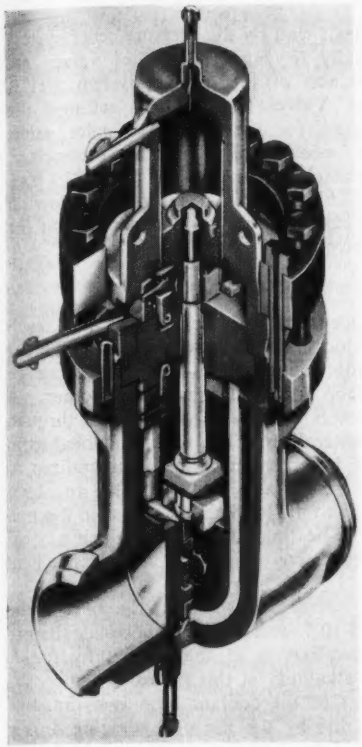
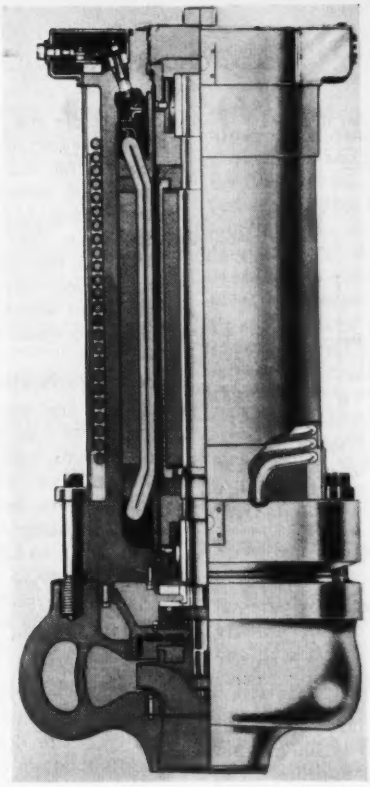
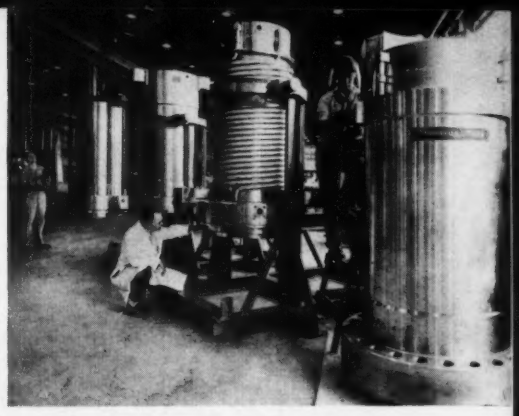


Fig. 9.—Heat exchangers. (Above) U-tube type (B. & W.). (Below) Straight-tube type (F.-W.).









(Left) Fig. 10.—Cut-away view of hydraulically-operated valve.

(Centre) Fig. 11.—Cut-away view of main coolant pump.

(Right) Fig. 12.—Pump assembly at Westinghouse works.

between the inner and outer thermal shield, the other through the annular space between the inner thermal shield and the outside of the core barrel. The two streams (each with a velocity of about 2 ft/sec) then rejoin the main stream above the flow guide.

The coolant next flows upward through the fuel assemblies (about 1% of the flow leaks past adaptor piston rings into the inactive spaces between assemblies). Approximately one-third of the coolant flows through the seed assemblies at a velocity of 20 ft/sec while the remainder flows through the four blanket regions at velocities ranging between 4.5 to 13 ft/sec.

Since the rods in the blanket regions and the plates in the seed region have very different hydraulic characteristics, the blanket region is orificed and, as the heat generation varies in different parts of the blanket, not all blanket assemblies require the same amount of throttling and the blanket is sub-divided into four regions. To keep the velocity below 50 ft/sec through the orifices and minimize erosion, the orifice unit which is located at the bottom of a blanket assembly, has several orifices in series. The orifice unit can be removed and replaced when the blanket assembly is taken out of the reactor vessel. This is desirable because changes in power distribution in the blanket, due to plutonium build-up, might require a flow redistribution during core life, and the blanket is expected to last more than one seed life.

About 2.5% of the total flow is used to cool the control rods in each of the seed assemblies. The water streams from the seed and blanket assemblies rejoin in the upper plenum, flow upward through the inside of the core hold-down barrel, then downward through the annular space between the hold-down barrel and the vessel wall, and finally discharge into the coolant loops through the outlet nozzles of the vessel. From there the coolant passes to the heat exchanger equipment.

TABLE 3

Comparison of Foster Wheeler and Babcock & Wilcox Heat Exchangers.

	F. W.	B. & W.
No. of tubes	2,096	921
Length	31 ft	50 ft
Outside diam.	½ in.	⅝ in.
Diam. of shell	43 in.	38 in.
No. of risers	12	18
Size of "	8 in.	5 in.
No. of downcomers	6	14
Size of "	8 in.	4 in.
Material of heat exchanger heads	Stainless Steel	Stainless clad carbon steel
Steam separation	48 separators, 20 driers	30 separators, 2 rows secondary scrubbers

Primary Coolant System

The coolant loop system is shown in Figs. 1 and 15. Each primary loop consists of a heat exchanger, pump, and four shut-off valves, two hydraulically operated, inside the reactor enclosure, and manual- or motor-operated valves in the heat-exchanger enclosure. The general particulars of the coolant loop are given in Table 2.

Heat Exchangers

The four heat exchangers are of two different types, each comprising a steam drum connected by a number of riser tubes to the shell and tube heat-exchanger portion. Two of the units, manufactured by Foster Wheeler, utilize straight tube bundles within the exchanger shell; the other two, by the Babcock and Wilcox Company, utilize a tube bundle and exchanger shell arranged in U formation. The two types of heat exchanger are illustrated in Fig. 9, and the salient design features are given in Table 3. In both systems, the maximum moisture content is given as 0.25% at full design capacity.

The main pumps are of the canned type, completely eliminating leaks by enclosing the stator and rotor in

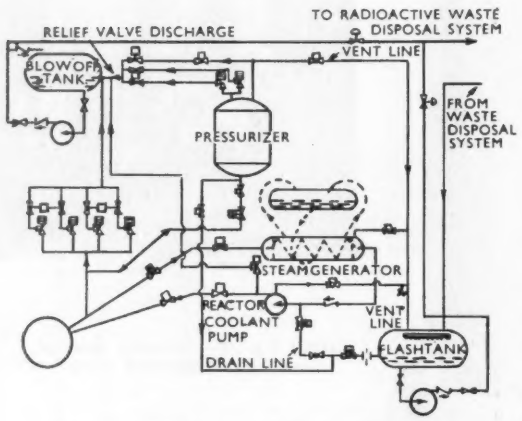


Fig. 13.—Simplified diagram of pressure relief system.

corrosion-resistant cans. The stator is cooled by external cooling coils; the rotor and bearings run in the primary water. There is, therefore, no need for a shaft seal, and the motor is bolted and seal-welded to the pump casing, making a completely leakproof unit.

This design of pump can operate at flow conditions ranging from 10,000 gal/min at 145 p.s.i. to 18,300 gal/min at 116 p.s.i., although not with the same impeller. The motors are two-speed single winding, the power input to each pump being 1,400 kW (approx. 1,870 h.p.).

Valves

Each loop has two hydraulically operated valves inside the reactor enclosure, these being of the type shown in Fig. 10. Both inlet and outlet valves are backed up with motor-operated valves outside the reactor enclosure. The gate opening in both valves is approximately 13 in., to keep the valve dimensions, and costs, reasonably low.

Each loop has, in addition, an 18-in. swing check valve, to prevent excessive backflow if the pump stops, while offering low resistance to normal flow. Small holes in the disc permit a certain amount of backflow, to avoid cold water—with consequent risk of excessive reactivity—being circulated in the event of the pump re-starting accidentally.

Piping

The main-loop piping is 15 in. i.d. and 18 in. o.d. stainless steel, hollow forged, turned and bored to a finish of 125 μin. r.m.s. on the inside and 250 μin. on the outside.

Pressurizer

The pressurizer is 18 ft high and 5 ft i.d., with a total volume of 260 cu. ft. During normal operation (2,000 p.s.i.) the steam bubble inside the vessel occupies approximately 146 cu. ft at a temperature of 636° F.

Heat for maintaining the steam bubble is provided by banks of immersion-type heating elements, with a total loading of nearly 850 kW, although in normal working only 360 kW is in operation, 60 kW being permanently on and 300 kW cycling on and off as required by changes in coolant volume.

A rise in pressure is counteracted by a spray system in the bubble space. Between them the spray system and the heaters can maintain pressure within the limits of 1,850 and 2,180 p.s.i.a. for the normal maximum-load changes; +15 MW or −12 MW as a step change; ±15 MW at 3 MW/sec; ±20 MW at 25 MW/min.

In case of sudden loss of load or pumping power, excessive pressure rise is dealt with by the pressure-relief system shown diagrammatically in Fig. 13. Relief valves are provided on each section of the coolant system that is capable of isolation. Valves have graded settings, the lowest being 2,175 p.s.i. for the pressurizer pilot valve, 2,260 p.s.i. for the second valve on the pressurizer; 2,450 p.s.i. for the reactor pressure vessel, and 2,830 p.s.i. for the loop valves. All water is released to a blow-off tank, from which it can, if necessary, be pumped to the radioactive waste system.

Coolant Purification

There are two identical purification circuits, each normally serving two loops, but capable of dealing with the requirements, and cross-connected so that coolant can be admitted from one loop and discharged into another. A portion of the coolant is continuously by-passed through the ion exchange demineralizer. The water is cooled from about 508°F to 120°F before entering the demineralizer, to avoid damage to the resins, and then re-heated to about 435°F before returning to the loop circuit, to avoid thermal shock. Cooling and re-heating take place in a pair of heat exchangers, on a regenerative basis, to avoid excessive heat wastage.

In order to avoid corrosion problems, the pH of the water is raised to 9.5-10.5 with lithium hydroxide before start-up. The demineralizer is of the lithium hydroxide type to maintain the alkalinity at this figure.

The oxygen content of the coolant loop is maintained within satisfactory limits by the use of hydrazine during the initial start-up, and the addition of gaseous hydrogen at the rate of 25 cm^3/kg during operation, to compensate for the oxygen formed by decomposition of the water. Continuous sampling and analysis of oxygen content is carried out.

F.E.D.A.L. System

The Failed Element Detection and Location System is intended for monitoring the blanket elements only, for delayed neutrons. Sample tubes from each of the 113 elements are led to a multi-port valve in the pressure-vessel head. Samples from two elements at a time are routed to separate monitoring systems, the remaining samples being by-passed.

It was originally anticipated that a hole as small as 0.005 in. would be detectable, but the uranium content of the zirconium canning has contributed an unexpected amount of background, and the sensitivity, although adequate, is not as good as was anticipated, and it appears that it will not be possible to obtain the original test results without the use of uranium-free zirconium for canning.

Other Auxiliary Systems

The chemical addition system can also be used for injecting boric acid into the main coolant under emergency conditions, such as control-rod failure.

In the event of a coolant-pump failure, shut-down of the reactor would occur, but there is still the residual heating of the reactor to be dissipated. A certain amount of coolant flow would take place by natural convection. The heat from this can be dissipated by relief valves in the secondary system, set at 707 p.s.i.a., and designed to dissipate 7 MW of heat in the form of secondary steam. The valve is normally isolated, but automatically placed in operation on the failure of the coolant-pump main supply.

A coolant charging system is provided to fill the primary system before operation and to flush out the system if required.

Lastly, there is a safety injection system, for use in serious emergency, such as a burst coolant pipe, when the reactor is losing water at a greater rate than the charging pumps can accommodate.

STEAM PLANT AND TURBINE

Each of the steam lines from the heat exchangers contains two relief valves, a balanced check valve to guard against reverse flow, manual- and motor-operated stop valves, and the venturi tube associated with the feedwater control regulator. A common steam receiver is provided for the four steam lines, and two steam lines from this feed the turbine.

Auxiliary steam plant such as turbine auxiliaries, station services and heating are fed from the main steam through a reduction valve. An auxiliary boiler is provided for use when the reactor is not in operation.

Turbine

The Shippingport turbine presented a number of problems in design. It is of a size (100 MW) that, until a comparatively short time ago, would have been considered large even for 1,500 p.s.i. 1,000°F conditions, while it is, of course, called upon to operate at 60 MW with saturated steam as low as 545 p.s.i., and is designed for a maximum flow of 1,300,000 lb/h, although the normal flow for 60 MW is 860,000 lb/h.

Normal expansion techniques for superheated steam would result in a moisture content at the exhaust end of 18-21%. The method adopted at Shippingport is that of extracting the steam part way and removing moisture by means of a stationary cyclone separator.

The turbine, shown in section in Fig. 14, is a single-cylinder 1,800-r.p.m. unit with a single stage of impulse blading in the approximate centre of the unit, with five-valve nozzle control for loads up to 80 MW. Above this, the first stage is by-passed. There are 16 stages of reaction blading in the high-pressure portion of the rotor, after which the steam leaves to the moisture extractor, afterwards returning to the approximate centre of the unit for the LP section, of which there are eight stages, the last-row blading being 40 in. long. The central steam entry, with opposite direction of flow for HP and LP sections, (although the design resulted from the impossibility of housing the connections to and from the steam separator) gives a considerable reduction in the amount of dummy pistons required for thrust balance, reducing leakage.

Stellite strips are provided on the inlet edges of all blades having tip speeds in excess of 900 ft/sec. In addition, all casing-blade bores are protected against erosion by a ¼-in. cladding of 18/8 stainless steel.

There are three bleed points for feedwater heating, one being in the HP section, one at the exit to the separator, and the third in the LP section. The turbine heat rate at 100 MW is 11,470 BTU/kWh.

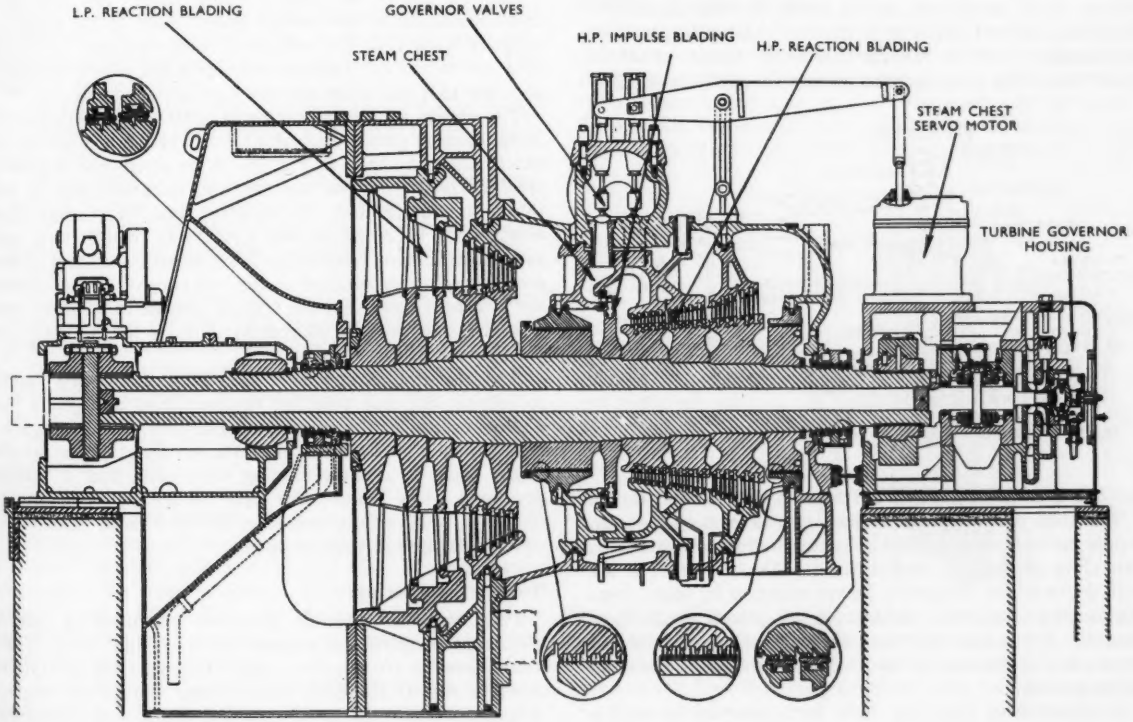
Moisture Removal

The steam separator consists of a cylindrical shell with an inlet pipe at one end into which is directed the apex of a cone-shaped or helicoid tuyere, the vanes of which impart a swirling motion to the steam, thus causing the water droplets to be thrown outwards by centrifugal force. The outlet projects from the other end, forming an annular space into which the water passes, being drained off and passed to the feedwater heating system. The outlet itself is fitted with radial vanes on the outside to prevent water flowing upstream and interfering with the vortex pattern of the steam. The moisture content of the steam is reduced from 11.6% to approximately 1%.

Condenser and Feedwater System

The turbine is located outdoors, with a walk-in type weatherproof housing over the governor gear. The

Fig. 14—Section of turbine.



condenser and auxiliary equipment is located beneath it. The condenser has 10,280 tubes with an effective cooling surface of 70,000 sq. ft. Auxiliaries include a two-stage steam-jet air ejector, and two 59,000-gal/min mixed-flow circulating-water pumps.

A 50,000-gal water storage tank supplying a minimum of one plant volume (25,000 gal) is used as the system reserve capacity. Normally, tank level is automatically maintained by condensate make-up from the deaerator. The system can furnish a maximum of 6,000 gal per day of demineralized, deaerated water as make-up for the reactor plant at a maximum rate of 15 gal/min, if required.

The boiler feed-water system uses two pumps of equal capacity to provide up to 1,400,000 lb/h of feed water to the four boilers. The total flow is greater than the maximum steam-generating rate, to allow for blowdown losses and to ensure that the boilers are fed under all conditions. Provision is made for a maximum boiler blow-down flow of 5,000 lb/h from each boiler to a flash tank in the turbine room basement. The boilers can also be drained to this tank—or if the water is contaminated, to the reactor plant waste disposal system after the water has been cooled to 150°F. Two water samples are continuously drawn from each boiler at a rate of $\frac{1}{8}$ gal/min to check for tube leaks (primary to secondary) in the steam generator.

A three-element feed-water control system maintains the water level in each steam drum within 2 in. of normal operating level with a load change in either direction not exceeding 20% per minute of the full rating of the plant for all power levels above 25 MW. As a secondary function, the system can deliver water to the safety injection system when the latter is in operation.

CONTROL AND INSTRUMENTATION

The control rods of the PWR are of crystal-bar hafnium which has good mechanical and corrosion resisting properties. The rods are of cruciform section approximately $3\frac{1}{4}$ in. across tips, and fit inside the seed assemblies. There are 32 rods each with its own individual operating mechanism, with a normal operating speed of about 11 in./min, with instantaneous release for scramming. Each

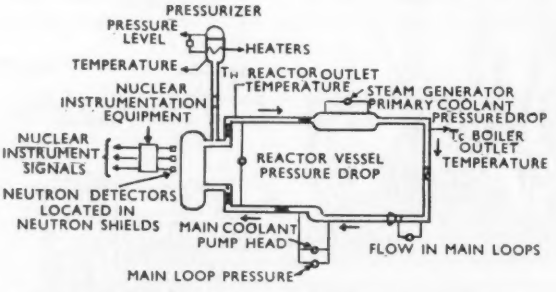


Fig. 15.—Schematic diagram of coolant loop instrumentation.

rod has a value of about 1% reactivity over its full travel.

The rods are attached to lead screws passing through 4-pole canned, water-cooled induction motors into housings extending above the reactor head. The motors are fed with 3-phase low frequency power supplied by eight commutator-type inverter units, each of which feeds four motors. For scram operation the springs which hold the drive nuts to the lead screw are released and the rods fall under gravity.

Coefficients of reactivity have been assessed as having

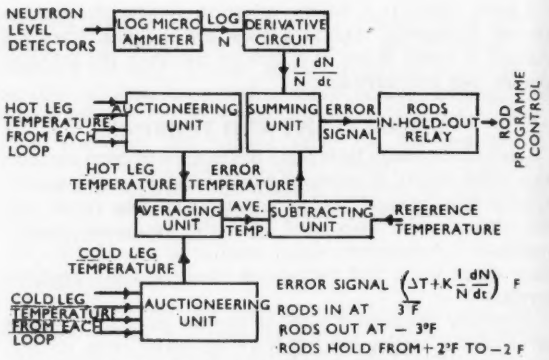


Fig. 16.—Block schematic of control system.

minimum values of $-2{\cdot}0.10^{-4}$ δk/°F for temperature and $+2{\cdot}4.10^{-6}$ δk/p.s.i. (pressure). Maximum speed of travel of the control rods except for emergency shut-down is limited to a rate equivalent to $7{\cdot}3.10^{-4}$ δk/sec.

The inherent negative temperature coefficient of the PWR considerably simplifies the problem of control, since the power level becomes largely self-regulating. In normal operation, control rod movements are used primarily to correct the gradual drift in coolant temperature caused by fission product variation; they may also be used to assist in speeding up the restoration of normal operating conditions following unusually large load changes. Of the 32 rods 12 are intended to remain fully inserted, being withdrawn only as necessary to compensate for xenon build-up. The remaining rods are withdrawn in groups of four.

The control philosophy of the PWR is based on the maintenance of constant average temperature of the primary coolant loop. Rod movement is initiated at ±3°F variation from normal, and halted at ±2°F, damping being built into the control system to prevent hunting.

Fig. 15 shows, in diagrammatic form, the principal instrumentation of the coolant loop. Each of the primary loops is fitted with five resistance thermometers, of which four are of the fast-response type and the fifth is a highly accurate unit that calibrates the fast response unit.

The system for determining and controlling operation by integration of power and temperature changes is shown in block schematic form in Fig. 16. Rate of change of power level, derived from the neutron level measurement, is fed into a summation unit. At the same time the average loop temperature is compared with a reference temperature, and the resultant error supplied to the summation unit. The net error signal is transmitted to the rod control system unless the system decides that the rate of change of neutron flux is such as to provide correction without the necessity of rod movement.

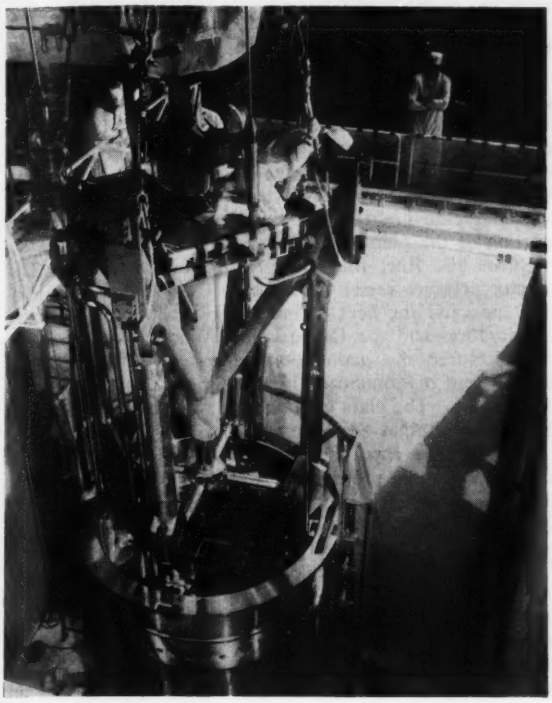
An interesting feature is the use of " auctioneering " units to receive hot and cold leg temperatures, and select the highest values for the computation of average temperature. This avoids an undesirable increase in reactor power which might occur if a single reading were used, and it should develop a " low " error. An error on the high side would, of course, lead to false operation but in a " safe " direction, i.e., a reduction in reactor power.

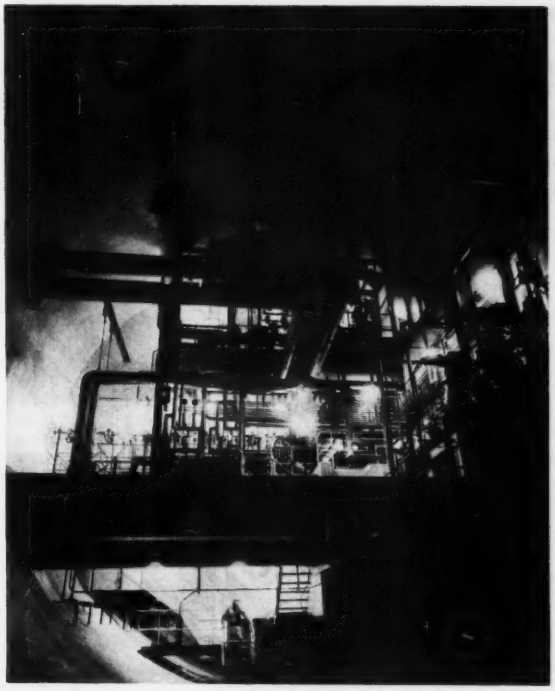
Neutron Monitoring

Two types of neutron monitors are used, a boron trifluoride proportional counter to cover the range from source level to $10^4\times$ source, and a compensated ionization chamber for 10^3 to $10^{10}\times$ source level. These are located in detector wells outside the pressure vessel, thus measuring

(Right) Fig. 17.—View inside auxiliary plant containment.

(Below) Fig. 18.—Lowering core and core cage into position.





leakage flux, about 10^{-4} of the average flux density in the core.

Radioactivity Monitoring

Measurement of radiation levels throughout the plant is carried out by a multi-channel system with computer indication providing read-out in the control room. The channels are as follows:—

(1) Four channels with gamma-sensitive Geiger tubes to detect primary to secondary water leaks in each steam generator.

(2) Gamma-sensitive ion chambers to determine activity in each of the four boiler chambers.

(3) A gamma-sensitive Geiger tube to detect leakage of primary coolant into the component cooling water system.

(4) Four beta-gamma-sensitive Geiger tubes to determine the gross activity (both gases and airborne particulates) in the air exhaust stack for the plant container.

(5) Four channels which use a filter paper system and scintillation counters to monitor the activity of the air in the plant chambers.

(6) Six access cubicles are monitored for limited personnel access.

Health Monitoring System

This system determines any increases in the normal background of the plant surroundings, and areas normally occupied within the plant buildings. Hand and foot monitors are also used, and monitors provided at exits. Film badges and dosimeters are provided for all personnel to record cumulative doses of radiation.

A programme of continuous monitoring of the environment outside the plant buildings including integrating ionization chambers, mobile off-site stations, and river sampling stations has been under way since early 1956 to obtain data on the types and amounts of radioactive materials occurring in the site environs, and to measure variations in this normal background radiation, so that it can be seen if any significant changes in normal background radiation occur due to station operation.

Remote Viewing System

This system is composed of two parts. One part has five television cameras to view areas within the chambers during operation. One is located in each of four boiler compartments and one in the pressurizer compartment. Camera tilt, swing, and focus are remotely adjustable from the control room. One monitoring receiver is used; it can be switched to any one of the five cameras. The other part of the system has four fixed-position, fixed-focus cameras adjusted to view the four boiler drum-level gauge glasses and four television monitors (one for each camera) in the control room.

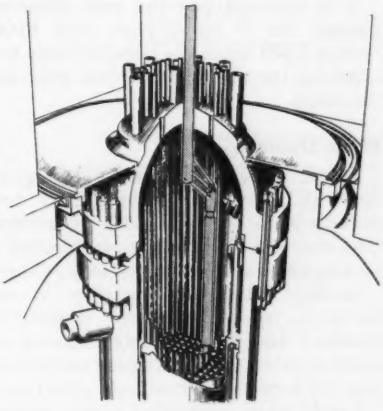


Fig. 19.—Simplified diagram showing method of fuel charging through one of the ten fuel ports in the reactor head.

Fuel Handling

Figs. 19 and 20 give a general idea of the arrangements for handling fuel elements into and out of the reactor. The fuel handling building—the largest single building on the site, with dimensions of 182 ft long, 44 ft wide, and 60 ft high—contains a fuel handling canal above the level of the reactor enclosure, and provided with several compartments or "locks" that can be separated from each other and used either dry or filled with water. The areas in the canal include one where fuel can be stored, another where cores can be dismantled, a transfer canal, and other storage pits, so that all components can be handled under water in safety.

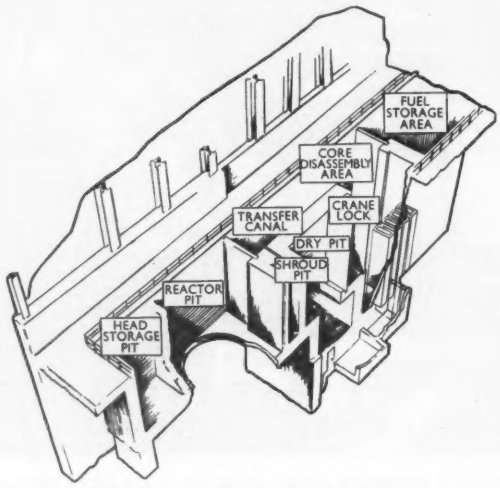


Fig. 20.—Diagram showing layout of fuel handling canal.

Fuel renewal may be by complete replacement of the core, which will need the removal of the vessel head. Alternatively, individual elements may be replaced, in which case this is done as shown in Fig. 19. The handling device is inserted through the fuel port in the reactor head, indexed to the correct angle, and the arms extended to the correct amount. The head is designed so that the fuel element can be unlocked from the core and locked to the handling tool.

It is expected that the seed elements will be charged through the 10 access ports after 3,000 hours. After a further 5,000 hours the complete core will be changed, this involving the cutting of the seal weld securing the head of the vessel.

Waste Disposal

Liquid effluent is piped to underground stainless steel tanks and stored while the activity decays, or processed through demineralizers and a gas stripper. If within permissible limits, the liquid can be blended with the condenser cooling water and discharged to the Ohio River.

Soluble radioactive impurities as well as particulate matter are removed in a series of mixed bed demineralizers, dissolved fission gases being removed in a steam stripper under slight vacuum and stored in steel tanks until they have decayed enough to permit safe discharge to atmosphere.

Liquid waste containing highly concentrated impurities, i.e., the fluids used for decontaminating equipment and facilities, are processed through a vapour compression evaporator. The distillate from the evaporator is sent to the liquid surge tanks and the concentrate mixed with cement and drummed for burial at sea. Spent demineralizer resin, principally from the internal purification system, is diverted by water to permanent underground stainless steel storage tanks in which the solids settle, the water being decanted to the liquid decay tanks for further processing.

Contractors

By sub-contract to Westinghouse, the Stone and Webster Engineering Corporation has provided the architect-engineer services for the nuclear portion of the plant. The Dravo Corporation of Pittsburgh, also under sub-contract to Westinghouse, installed the nuclear plant. Burns and Roe, Inc., and Associates acted as agent-constructor for the Duquesne Light Co. in building the turbine-generator portion of the plant.

Burns and Roe, Inc. acted as agent-constructors. The reactor pressure vessel was built by Combustion Engineering, Inc., and the heat exchangers by the Foster Wheeler Corporation and the Babcock and Wilcox Co., who also manufactured the main coolant piping. Main coolant valves were manufactured by the Crane Co. and Edward Valves, Inc. The plant containment was made by the Pittsburgh-Des Moines Steel Company.

As might be expected with an experimental station, an elaborate testing programme was laid down during the design. Four test periods: installation, precritical, initial critical and full power operation have already elapsed. Tests planned for the future will go beyond original design specifications to determine maximum plant and component capabilities and limitations. New methods of operation and maintenance will be investigated; useful design changes or developmental equipment will be checked. The performance of the station as a unit in the Duquesne system will be observed. Detailed information on core handling and on core performance from the viewpoint of physical, thermal and control technology will be obtained, and experience from extended runs at power will add to fundamental reactor and reactor plant knowledge.

Costs

The following data give a brief summary of the make-up of operating costs:—

CAPITAL INVESTMENT

Nuclear plant construction cost (not including core)	$42,000,000
Nuclear plant design and engineering	8,500,000
Turbine-generator plant, Duquesne Light	17,500,000
	$68,000,000

Annual fixed charge=14%=$9,520,000.
Plant output/year=420×10^6 kWh.
Capital contribution to power cost=22.7 mills/kWh.

FUEL COST

Fissionable materials		
Blanket, 14.6 tons nat. UO_2 at $40.50/kg		$537,000
Seeds, 182 kg enriched U at $16,000/kg	$2,912,000	
Processing loss	364,000	
		$3,276,000
A.E.C. use charge (4%/y)		
Blanket, 2½ y	$54,000	
Seeds, 2 y	262,000	
		$316,000
Fissionable materials total		$4,129,000
Fabrication and nonfissionable materials	$14,200,000	
Use of facilities, 14% of $4,400,000	616,000	
		$14,816,000
Fuel inventory carrying charge		1,895,000
Total fuel cost		$20,840,000

Total net power produced, 480×10^6 kWh.
Cost of fuel per kWh, 43.4 mills.

SUMMARY OF ESTIMATED COST OF POWER

	mills/kWh
Capital investment	22.7
Fuel	43.4
Operations	3.3
Total	69.4
Fuel credits	5.0
	64.4
	use 64 mills/kWh

Acknowledgment is made to the *Westinghouse Engineer* for a number of the diagrams in this article.

Nuclear Engineering
DATA SHEET
No. 8. Molybdenum and Tungsten

MOLYBDENUM AND TUNGSTEN

	Mo	W
Symbol	Mo	W
Atomic number	42	74
Atomic weight	95.95 (4)	183.92 (4)
Atomic volume	9.41 cm^3/g atom (10)	9.53 cm^3/g atom (4)
Atomic radius	1.367×10^{-8} cm (6)	1.359×10^{-8} cm (6)
Lattice type	Body-centred cubic	Body-centred cubic
Lattice parameter	3.140×10^{-8} cm (3)	3.159×10^{-8} cm (2) (9)
Density at 20°C	10.22 g/cm^3 (10)	19.3 g/cm^3 (1)
Thermal expansion	Table 1	Table 1
Thermal conductivity	Table 2	Table 2
Specific heat	Table 3	Table 3
Neutron capture cross-section	Table 7	Table 7
Vapour pressure	Table 4	Table 4
Electrical resistivity	Table 5	Table 5
Surface tension	2,240 dyne/cm (19)	2,300 dyne/cm (18)
Emissivity	Table 6	Table 6
Melting point	2,622±10°C (11)	3,410±10°C (12)
Hardness at 20°C	—	Table 8
Mechanical properties	Table 9–12	—
Creep properties	Table 13	—
Elasticity moduli	Table 14–15	Table 14–15
Poisson's ratio	0.324 (24)	0.284 (1)
Bulk modulus	—	46.3×10^6 $lb/in.^2$ (1)
Isotopes	Table A & B (in text)	Table A & B (in text)
Compatibility	Table 16–17	Table 16–17

PHYSICAL PROPERTIES

TABLE 1
Thermal Expansion Coefficient (per °C)

Temperature °C	Molybdenum (16)	Tungsten (17)
25	4.9×10^{-6}	4.44×10^{-6}
1,000	6.1×10^{-6}	5.19×10^{-6}
2,000	7.1×10^{-6}	7.26×10^{-6}

TABLE 2
Thermal Conductivity cal/sec, cm, °C (15)

Temperature °C	Molybdenum	Tungsten
20	0.382	0.31
927	0.259	0.275
1,127	0.23	0.268
1,327	0.202	0.26
1,527	0.173	0.253

TABLE 3
Specific Heat cal/g, °C

Temperature °C	Molybdenum (14)	Tungsten (1)
0	0.0589	0.0328
500	0.0750	0.0339
1,000	—	0.0362

TABLE 4
Vapour Pressures and Temperatures (13)

Vapour pressure mm Hg	Temperature °C	
	Molybdenum	Tungsten
10^{-3}	1,923	2,554
10^{-4}	2,095	2,767
10^{-5}	2,295	3,016

TABLE 5
Electrical Resistivity microhm, cm

Temperature °C	Molybdenum (16)	Tungsten (17)
25	5.78	5.65
500	18.4	18.51
1,000	32.2	33.29
2,000	68.6	65.82

TABLE 6
Total Emissivity

Temperature °C	Molybdenum (16)	Tungsten (17)
500	0.084	0.074
1,000	0.133	0.156
2,000	0.239	0.286

TABLE 7
Neutron Capture Cross-sections

Neutrons	Molybdenum	Tungsten
Thermal	2.5 b (20)	18 b (20)
0.1 MeV	2—3 b (21)	4—6 b (21)
1.0 MeV	1 b (21)	1—3 b (21)

MECHANICAL PROPERTIES

TABLE 8
Tungsten: Hardness at Various Stages of Reduction (1)

Material	Diamond hardness number
Sintered bar 9×9 mm	255
Swaged to 8.0 mm	400
Swaged to 5.0 mm	407
Reheated to 2,700°C	392
Swaged to 3.5 mm	474
Swaged to 2.7 mm	483
Swaged to 1.8 mm	448

See also Fig. 4

TABLE 9
Mechanical Properties of Arc Cast Molybdenum Hot Rolled to ½ in. dia Bars (24)

Annealing temperature °C	Yield point $lb/in.^2$	Tensile strength $lb/in.^2$	Elongation %	Reduction of area %	V.P.N.
Hot rolled	99,800	100,100	32	60.9	255
925	—	91,700	39	59.2	—
1,040	84,700	90,600	41	65.7	—
1,150	54,100	73,100	53	64.2	187
1,200	50,100	73,600	55	55.6	187

TABLE 10
Tensile Strength of Molybdenum Wire Showing Progressive Increase as Drawn to Finer Sizes (25)

Diameter in.	Tensile strength 10^3 $lb/in.^2$
0.005	200–260
0.0028	230–270
0.0015	270–310

TABLE 11

Tensile Strength of Molybdenum at Different Temperatures (24)
Arc-cast Hot Rolled to ½ in. dia Bars

Testing temperature °C	Condition	Tensile strength lb/in.²	0.2% yield strength lb/in.²	Proportional limit lb/in.²	Elongation in 2 in. %	Reduction of area %
27	As rolled ..	95,140	—	—	3	2
	Stress relieved ..	91,000	84,850	—	10	9
	Recrystallized ..	67,600	63,500	—	46	36
870	As rolled ..	61,400	50,100	26,000	18	72
	Stress relieved ..	50,600	44,500	21,500	22	81
	Recrystallized ..	34,400	11,600	3,500	46	84
980	As rolled ..	49,900	40,500	23,000	19	81
	Stress relieved ..	40,500	35,600	22,500	32	81
	Recrystallized ..	29,000	10,500	5,700	49	75
1,065	As rolled ..	38,000	31,600	24,000	29	83
	Stress relieved ..	31,400	22,800	16,500	36	84
	Recrystallized ..	21,500	8,550	4,100	35	52

TABLE 12

Molybdenum: Stress Rupture Strength (100 hour) of Wrought, Arc-cast Material (28)

Condition	Temperature of test		
	870°C	980°C	1,095°C
Stress relieved ..	31,000 lb/in.²	18,000	10,000
Recrystallized ..	16,000	11,500	9,000

TABLE 13

Molybdenum: Creep at 1,000°C at 5 tons/in.² on ½ in. dia Bars (27)

Type of test	Total creep strain %		Creep rate % 10–100 hour
	0–24 hour	0–100 hour	
Compression ..	0.76	0.96	0.0032
Tensile	0.65	1.00	0.0055

TABLE 14

Young's Modulus (Wires <0.1 mm)

Temperature °C	Modulus lb/in.²	
	Molybdenum (24)	Tungsten (1)
0	$45–46\times10^6$	$49.5–55.2\times10^6$
890	39×10^6	—
1,000	—	46.5×10^6

TABLE 15

Rigidity Modulus (Wires <0.1 mm)

Temperature °C	Modulus lb/in.²	
	Molybdenum (24)	Tungsten (23)
0	17.4×10^6	$23–26\times10^6$
890	15.1×10^6	—

COMPATIBILITY

TABLE 16

Compatibility with Uranium

Molybdenum			Tungsten		
Compatible to about 750°C (8)			Compatible to about 1,000°C (8)		
Temperature °C	Duration of test	Penetration (in.)	Temperature °C	Duration of test	Penetration (in.)
900	6 weeks	0.009	1,250	8 hours	nil
1,000	2 weeks	0.013	1,300	9 hours	0.005
1,050	100 hours	0.010	1,350	2 hours	0.010
1,150	10 hours	0.005			
1,200	1 hour	0.045			
1,250	15 minutes	0.055			

TABLE 17

Compatibility of Molybdenum and Tungsten with Various Materials and Coolants

Material or coolant	Molybdenum	Tungsten
Hydrogen .. } Helium .. }	Compatible at all temperatures.	Compatible at all temperatures.
Nitrogen	Compatible to at least 1,000°C.	Compatible to at least 1,000°C.
Carbon Dioxide ..	Promising compatibility at 500°C. At 500°C, 8 atmospheres pressure, surface film of brown MoO_2 formed. Rate of oxidation uneven but approximates to cubic law. 90 day weight gain: 0.65 mg/cm² (22).	Promising compatibility at 500°C. Weight gain of 0.4 mg/cm² after 94 days at 500°C in 8 atmospheres CO_2. Oxidation rate uneven but may approximate to linear law (22).
Ammonia	Forms nitride at red heat.	Forms nitride at red heat.
Steam .. } Air .. .. }	Serious attack above 450°C due to formation of volatile MoO_3.	Serious attack above 450°C due to formation of volatile WO_3.
Hydrocarbons ..	Forms carbide at red heat.	Forms carbide at red heat.
Water	Compatible.	Compatible.
Sodium and NaK ..	Compatible with pure Na or NaK up to at least 600°C. Exhibits sensitivity to oxygen impurity level in liquid metal.	Compatible with pure Na or NaK up to at least 600°C. Exhibits sensitivity to oxygen impurity level in liquid metal.
Refractory Oxides .. (including UO_2, ThO_2, BeO, MgO).	Compatible to at least 1,500°C.	Compatible to at least 1,500°C.

MOLYBDENUM and TUNGSTEN

Possibilities in the Nuclear Field

By M. DAVIS, B.Sc., Ph.D.
(Research Manager, U.K.A.E.A. I.G. Culcheth)

Molybdenum and Tungsten have high-temperature and other properties which may make them attractive as canning materials for some types of advanced nuclear reactors. Exploitation in this field may first require the development of suitable alloys.

THE metals molybdenum and tungsten are outstanding for their high-temperature characteristics. Such properties as high-temperature strength, high modulus, high thermal and electrical conductivities, low vapour pressure and low thermal expansion have made them particularly valuable in elevated temperature applications. They are indispensable in incandescent lamps and radio valves as filaments, electrodes, supports, springs and glass-to-metal seals. They are also extensively used as electrical contacts and, in vacuum or controlled-atmosphere, high-temperature furnaces, as resistance elements, susceptors, and radiation shields. Tungsten is widely used as a non-consumable electrode in arc welding. Molybdenum is well known for the strong bond it forms when flame-sprayed on to steel and light alloys. The greatest tonnage of these metals, however, is devoted to alloy steel making.

Hitherto, molybdenum and tungsten have hardly been used in nuclear reactors, but because of their almost unrivalled high-temperature properties and favourable compatibility with reactor materials and coolants, they must merit consideration for advanced reactors. In the case of tungsten this may be restricted to fast reactors, because of an appreciable thermal neutron capture cross-section. However, molybdenum has a slightly lower thermal neutron capture cross-section than stainless steel and may, consequently, be considered for thermal reactors.

Although both metals are readily available in bar, sheet and wire forms, tubes are difficult to fabricate and ductile welds are hard to achieve. Both metals exhibit a transition temperature from ductile to brittle behaviour, which is very sensitive to the presence of impurities. Recent work on molybdenum[30] has shown that judicious alloying can effect marked improvements in ductility. It is believed that both metals are capable of considerable development in fabricability and joining, but this development work is a necessary pre-requisite to the exploitation of the potentialities of these metals in nuclear reactors.

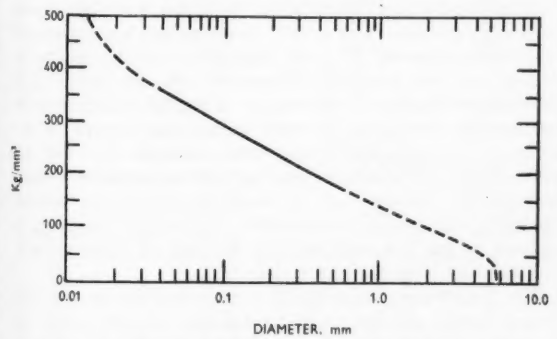


Fig. 1.—Tungsten. Tensile strength of wire showing progressive increase as drawn to finer sizes.

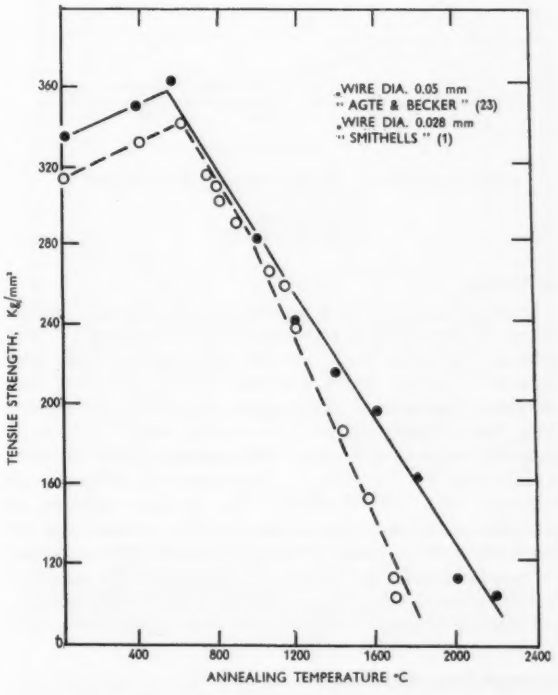


Fig. 2.—Effect of annealing on tensile strength of tungsten (1).

Occurrence

Molybdenum is about as abundant as lead (about $1.5 \times 10^{-3}\%$ of the earth's crust) and is found as two principal minerals: molybdenite, MoS_2, and wulfenite, Pb Mo O_4. It is widely distributed but the U.S.A. is the principal producer. The European deposits are in Scandinavia.

Tungsten is about five times as abundant as molybdenum. The commercially important ores are wolframite, Fe (Mn) WO_4, a ferrous manganous tungstate of variable Fe to Mn ratio and scheelite, Ca WO_4.

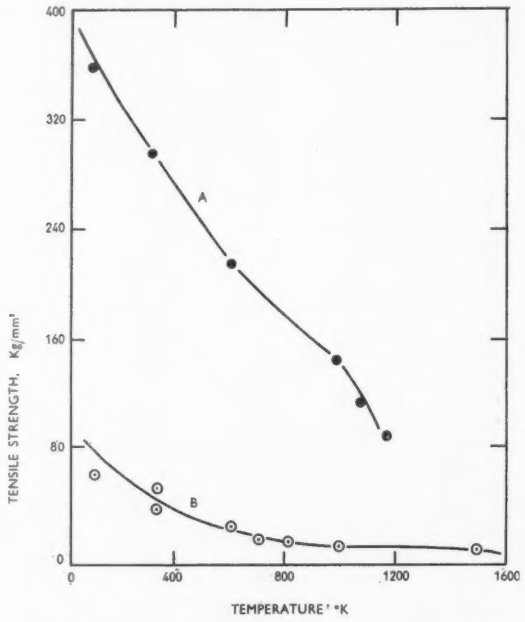


Fig. 3.—Tungsten. Tensile strength as a function of temperature (1).

A. Drawn wire.
B. Recrystallized wire.

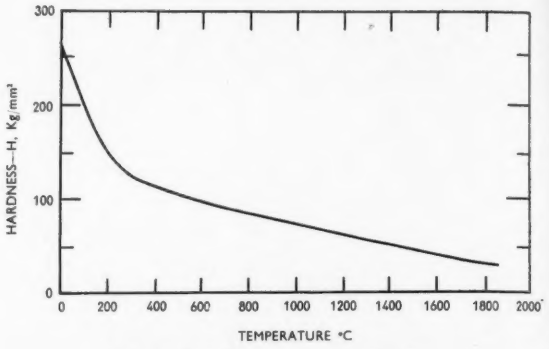


Fig. 4.—Tungsten. Hot hardness (1).

Extraction

In both cases the ores are low-grade, and are concentrated by ore-dressing techniques before shipment. The primary extractive stage for the preparation is the conversion to oxides which involves roasting of MoS_2 and chemical treatment to form tungstic acid with the tungsten ores. Both MoO_3 and WO_3 are volatile oxides and this is exploited in their purification. Reduction to metal powders is achieved by furnacing in hydrogen at temperatures between 700°C and 1,100°C. The precise schedule of reduction is carefully controlled, in order to determine the particle size of the metal product. The metal is consolidated by powder metallurgy techniques involving high temperature sintering in a hydrogen atmosphere. For molybdenum, arc melting of partly sintered bars is an alternative route.

Physical Properties

The physical properties of molybdenum and tungsten are given in the accompanying data sheet. Tungsten is the highest melting point metal and its density is among the highest. Both metals possess a high thermal conductivity (about a third of that of copper) and a low coefficient of thermal expansion. This combination is valuable in high-temperature work from a heat-transfer standpoint and also for minimizing thermally induced stresses.

Each metal has a number of natural and radioactive isotopes. None of the latter is long lived, nor are penetrating gamma radiations a problem. The implications of the values for neutron capture cross-sections have already been remarked above.

Mechanical Properties

Among commercially available metals, molybdenum and tungsten are probably unsurpassed for their high moduli and high-temperature mechanical properties. Other characteristics such as poor air oxidation resistance, have, however, restricted their exploitation as high-temperature materials to lamps and radio valves.

The low-temperature mechanical properties of these body-centred cubic metals are, like iron, dominated by a transition from ductile to brittle behaviour as temperature is reduced. The transition temperature is not a fundamental characteristic of the metal, but appears to be critically dependent upon the purity, grain structure and past history of the metal. Thus the curves of Fig. 6 should be taken only as illustrative of the effect, and not as immutable transition temperatures.

The addition of alloying elements to molybdenum has, in some cases, produced beneficial results in lowering the ductile-brittle transition temperature (Fig. 7). This is believed to be due to the neutralizing effect of these elements on harmful impurities.

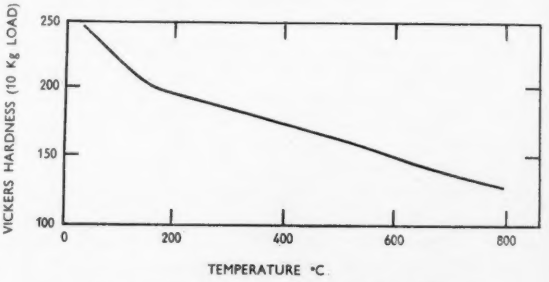


Fig. 5.—Molybdenum. Hot hardness (26).

At the present stage of development, it is not possible to assign unique values for such mechanical properties as tensile strength and elongation for these metals. The data which have been assembled show a progressive improvement in mechanical properties as the metal is worked down to smaller gauges. The actual values quoted are consistent with those obtained by good present-day production techniques, but are markedly dependent on the purity and fabrication history of the metal. Tungsten exhibits little measurable elongation at room temperature except in the form of fine wires and it then rarely exceeds 4%. On the other hand, molybdenum can possess appreciable room-temperature ductility up to over 50% for some forms. Ductility improves as temperature is raised and this fact is utilized in the hot working and shaping of these metals. A sensitivity to strain rate is detectable.

The high-temperature mechanical properties known are mainly tensile strengths and hardnesses. A little work on creep has been published on molybdenum, but hardly any on tungsten. Excellent creep behaviour would be expected.

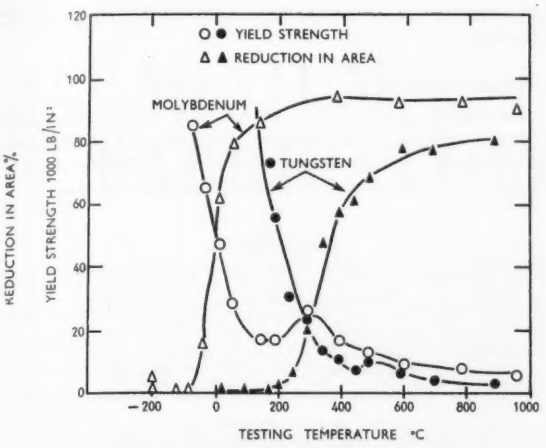


Fig. 6.—Transition from ductile to brittle behaviour as a function of temperature (29).

Annealing causes some softening and improvement of ductility, but if recrystallization occurs, practically all cold ductility is lost. The recrystallization temperature depends on the purity and history of the metal. Values of 900°-1,000°C for molybdenum and 1,100°-1,200°C for tungsten may be taken as typical for the onset of recrystallization in the worked metals.

Compatibility

The compatibility relationships with other materials of interest in nuclear reactors have only been determined in outline, but these have shown good promise. This information is summarized in Tables 16/17. Both metals are resistant to attack by hydrochloric and hydrofluoric acids, but are attacked by nitric and boiling sulphuric acids.

Fabrication

Current practice is to heat the " as sintered " bar (molybdenum can be as arc-cast ingot) in a hydrogen-atmosphere furnace to a temperature of 1,200°-1,400°C, and then reduce it by hot working (swaging, rolling or forging), depending upon the form of the product required. As the metal is progressively reduced by a sequence of heating and hot working operations, it becomes more amenable to lower-temperature working. The sequence of operations to yield a product to suitable grain structure, ductility, etc., is usually optimized and thereafter adhered to. Eventually, sheet may be rolled at a few hundred degrees centigrade and wire drawn cold.

Molybdenum sheet under 0.020 in. can usually be bent, sheared or formed cold, although it is often advisable to warm the metal and tools to 100°-200°C. Similar operations on tungsten need a temperature of 200°-350°C.

Deep-drawing and spinning has been accomplished successfully with molybdenum. Cross-rolled sheets give the best results and low friction-coefficient aluminium bronzes make the best tools. The process is usually best done warm, although some materials under 0.020 in. can be deep drawn cold.[7]

Machining of both metals is best done with tungsten carbide tipped tools, with tool angles similar to those employed with cast iron. Again, it is advisable to machine the tungsten at 200°-300°C. Grinding is fairly straightforward, but a copious supply of coolant is advisable.

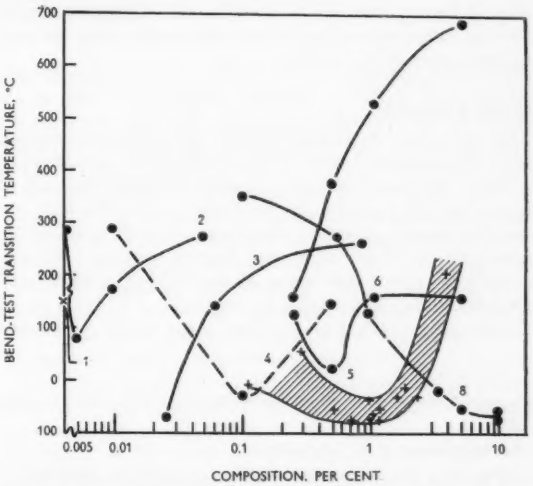


Fig. 7.—Effect of various elements on bend-test transition temperature of cast molybdenum. Bend tests made at a strain rate of 0·038 in. per in., per sec. (30).

1. Unalloyed molybdenum (5-10 ppm O_2); 2. Boron; 3. Aluminium; 4. Cerium; 5. Titanium; 6. Vanadium; 7. Zirconium; 8. Thorium. Al and Ti compositions are actual values; the remainder are the amounts which were added.

Molybdenum and tungsten may be joined by arc welding or brazing in hydrogen or inert gas atmospheres. Care has to be taken to prevent oxidation. This is particularly important in arc welding, since oxygen can give rise to excessive intergranular brittleness. At the present stage of development, welds, although sound, suffer from lack of ductility, usually consequent upon recrystallization. Ductile welds have been reported in molybdenum, but this is generally only possible with selected material, welded under closely controlled conditions.

Electrical resistance welding is widely employed, as a means of joining these metals in the radio valve and electric lamp industries. In these cases, joints are designed so that lack of ductility at welds does not give rise to unreliability.

A variety of brazing materials can be used

TABLE A
Natural Isotopes

Molybdenum (20)		Tungsten (20)	
Mass No.	% Abundance	Mass No.	% Abundance
92	15.7	180	0.14
94	9.3	182	26.2
95	15.7	183	14.3
96	16.5	184	30.7
97	9.5	186	28.7
98	23.8		
100	9.5		

TABLE B
Radioactive Isotopes

Molybdenum (20)				Tungsten (20)			
Mass No.	Decay	Half life	γ energy (MeV)	Mass No.	Decay	Half life	γ energy (MeV)
90	β^-	5.7 h	0.25	176	$k\beta+$	1.3 h	~1.3
91	$\beta+$	66 sec	1.54, 1.21	177	k	2.2 h	~0.5, 1.2
93		6.9 h	1.48	178	k	21 d	~0.3
99	β^-	67 h	0.74	179	k	30 min	
101	β^-	15 min	0.19, 0.96	181	k	140 d	0.137, 0.153
102	β^-	11 min		185	β^-	74 d	0.054
105	β^-	<2 min		187	β^-	24 h	0.072, 0.87
				188	β^-	65 d	

successfully for joining molybdenum and tungsten. Where high-temperature strength is not called for, brazing with copper or a silver alloy is satisfactory, especially if carried out in a reducing atmosphere of hydrogen or nitrogen plus hydrogen. Nickel and platinum have been used for higher temperature applications and recently molybdenum boride (m.p. 1,900°C) has been shown to make good brazed joints for high-temperature service. This latter material may only be suitable for nuclear applications if the low capture cross-section boron isotope (B^{11}) is employed.

Effect of Reactor Conditions

Molybdenum and tungsten have been irradiated at temperatures up to 100°C at doses of 5×10^{19} to 5×10^{20} n/cm^2, but no work seems to have been done at higher temperatures.[31, 32] The yield stress of molybdenum, and the fracture stress of tungsten, exhibit increases following irradiation. The ductile-brittle transition temperature of molybdenum is reported to show a marked increase under these conditions[32] but that of tungsten only slightly increased. It would be expected that the effect of irradiation would be less at temperatures at which these metals might be used in a reactor core.

General Remarks

The attractive high-temperature properties of molybdenum and tungsten make them worthy of consideration for use in advanced nuclear reactors, although the use of tungsten would probably be restricted to fast reactors, on neutron-economy grounds. Development work is called for in the fields of fabrication and ductile welding. Present knowledge suggests that many of the difficulties associated with these metals are related to impurities. In the case of molybdenum, which has received most study, promising improvements in properties have been secured by judicious alloying.

Acknowledgments

The author is grateful to Sir Leonard Owen, Managing Director and Dr. H. Kronberger, Director of Research and Development, Industrial Group, United Kingdom Atomic Energy Authority, for permission to publish this paper.

REFERENCES

1. Smithells, C. J. "Tungsten" (Chapman and Hall, London), 1952.
2. Li, K. C. and Wang, C. M. "Tungsten" (Reinhold, New York), 1947.
3. Northcott, L. "Molybdenum" (Butterworth, London), 1956.
4. "Rare Metals Handbook," Ed. Hampel, C. A. (Reinhold, New York), 1954.
5. Williams, D. and Yuster, P. *Phys. Rev.*, **69** (1946), 556.
6. Hume-Rothery, W. "Structure of Metals and Alloys," Inst. Metals, 1945.
7. Duckworth, F. *Machinery, London*, **84** (1954), 389.
8. McIntosh, A. B. and Bagley, K. Q. *J. Inst. Met.*, **84** (1956), 251.
9. Owen, E. A. and Iball, J. *Phil. Mag.*, **13** (1932), 1020.
10. "Arc Cast Molybdenum and its Alloys" Climax Molybdenum Co., New York, 1955.
11. Worthing, A. G. *Phys. Rev.*, **25** (1925), 846.
12. Nat. Bar. Standards. *Prop. Met. and Alloy*, Circ. C. 447 (1943).
13. Dushman, S. "Scientific Foundations of Vacuum Technique." (Wiley, New York), 1949.
14. "Handbook of Chemistry and Physics, 33rd edn., 1952." (Chemical Rubber Publ. Co., Cleveland.)
15. Osborne, R. H. *J. Op. Soc. Am.*, **31** (1941), 428.
16. Worthing, A. G. *Phys. Rev.*, **28** (1926), 190.
17. *Ibid.*, **10** (1917), 638.
18. Calverley, A. *Proc. Phys. Soc.*, **B70** (1957), 1040.
19. Taylor, J. W. *Metallurgia*, **50** (1954), 161.
20. General Electric Chart of Nuclides, 5th ed., April, 1956. (Knolls Atomic Power Laboratory.)
21. "Neutron Cross Sections" BNL 325 (1955). Brookhaven National Laboratory.
22. Tyzack, C. Unpublished Culcheth data.
23. Agte, C. and Becker, K. *Phys. Zeit*, **32** (1931), 65.
24. Parke, R. M. *Metal Progress*, **59** (1951), 81.
25. Fink, C. G. *Trans. Amer. Electrochem. Soc.*, **17** (1910), 229.
26. Bruckart, W. L., *et al. Trans. A.S.M.*, **45** (1953), 286.
27. Rendall, J. H., Johnstone, S. T. M. and Carrington, W. E. *J. Inst. Met.*, **82** (1954), 345.
28. Semchyshen, M. and Barr, R. Q., Climax Molybdenum Co. 4th Annual Rep. to U.S.O.N.R. (1953).
29. Bechtold, J. H. and Shewman, P. G. *Trans. A.S.M.*, **46** (1954), 397.
30. Olds, L. E. and Rengstorff, G. W. P. *J. Met.*, **9** (1957), 468.
31. Bruch, C. A., McHugh, W. E. and Hockenburg, R. W. *Trans. A.I.M.E.*, **203** (1955), 281.
32. Makin, M. J. and Gillies, E. *J. Inst. Met.*, **86** (1957), 108.

Le Molybdène et le Tungstène

Par suite de leurs propriétés hors ligne à des températures élevées et de leur bonne compatibilité avec les combustibles et réfrigérants nucléaires, le molybdène et le tungstène dont des candidats intéressants pour les matériaux d'emboîtage dans les réacteurs avancés. L'emploi du tungstène pourrait être restreint aux réacteurs à neutrons rapides par suite d'une coupe de capture élevée pour les neutrons thermiques et épithermiques. Toutefois, pour des raisons d'économies de neutrons, le molybdène est plus favorable que l'acier inoxydable.

Les deux métaux existent dans le commerce à des prix raisonnables, mais seulement sous les formes requises par leurs usagers principaux: les industries des lampes électriques et des lampes radio. Des travaux de développement s'imposent pour la production pratique de ces métaux sous forme de tubes, et il y a des difficultés à surmonter afin de produire des joints satisfaisants qui soient ductiles. Un grand nombre des difficultés rencontrées lors de la fabrication et de la soudure sont, croit-on, associées à la présence d'impuretés indésirables en traces, telles que le carbone, l'azote et l'oxygène. En ce qui concerne le molybdène au moins, l'addition d'éléments d'alliage qui ont tendance à neutraliser les effets de ces impuretés semble offrir des possibilités d'amélioration.

Molybdän und Wolfram

Molybdän und Wolfram sind von Interesse als Mantelmaterial für Brennstoffelemente in neuen Reaktoren wegen ihrer ausnehmend guten Eigenschaften in hohen Temperaturen, und weil sie sich gut mit Atom-Brennstoffen und Kühlmitteln vertragen. Die Verwendung von Wolfram könnte auf Reaktoren, die mit schnellen Neutronen arbeiten, beschränkt sein, weil es einen hohen Einfang-Querschnitt für thermische und nahezu thermische Neutronen hat. In Hinsicht auf Neutronen-Wirtschaftlichkeit ist Molybdän günstiger als rostfreier Stahl.

Beide Metalle sind im Handel zu angemessenen Preisen erhältlich, jedoch nur in der Form, in der sie in der Hauptsache gebraucht werden, nämlich für die elektrische Lampen- und Radio-Röhren-Industrie. Es erfordert weitere Entwicklungsarbeit, um diese Metalle in einfacher Weise in der Gestalt von Rohren zu fabrizieren, und weitere Schwierigkeiten sind zu überwinden, um gute und nachgiebige Verbände zu erhalten. Es wird die Meinung vertreten, dass viele Schwierigkeiten, die im Zusammenbau und beim Schweissen auftreten, auf die Gegenwart von unerwünschten Spuren von Verunreinigungen wie Kohlenstoff, Stickstoff und Sauerstoff zurückzuführen sind. Zumindest ist das so beim Molybdän, wo aber die Hinzufügung von Legierungsstoffen, die die Wirkung der Verunreinigungen zu neutralisieren im Stande waren, Möglichkeiten zur Verbesserung in Aussicht stellt.

Molibdeno y Tungsteno

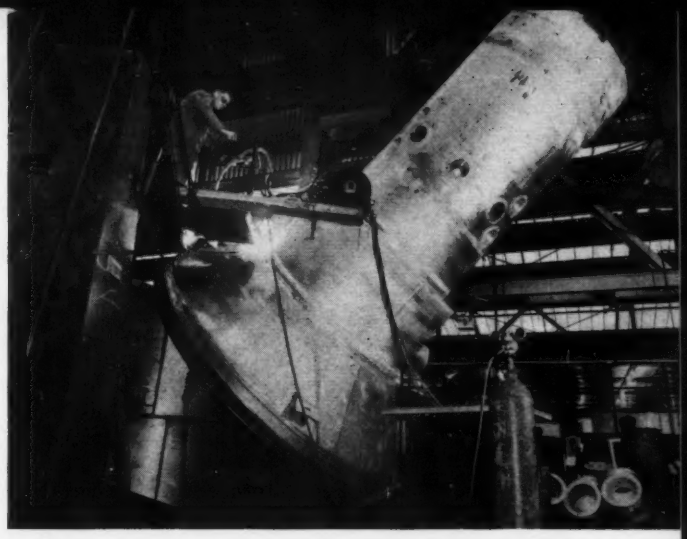
Debido a sus notables propriedades de altas temperaturas y buena compatibilidad con los combustibles y refrigerantes nucleares, el molibdeno y el tungsteno resultan interesantes candidatos para los materiales de envasamiento en los reactores avanzados. El empleo del tungsteno puede ser limitado a los reactores neutrónicos rápidos debido a una sección transversal de elevada captura de neutrones térmicos y epitérmicos. Sin embargo, teniendo en cuenta la economía en neutrones, el molibdeno resulta más favorable que el acero inoxidable.

Ambos metales se hayan disponibles comercialmente a precios razonables, pero únicamente en las formas exigidas por sus principales usuarios: las industrias de lámparas eléctricas y válvulas para radio. Es preciso, pues, hacer un trabajo de desenvolvimiento para producir estos metales fácilmente en forma de tubos, y hay que vencer ciertas dificultades para producir juntas satisfactorias que sean dúctiles. Se cree que muchas de las dificultades en la fabricación y soldadura están asociadas con la presencia de trazas de impurezas indeseables, tales como carbono, nitrógeno y oxígeno. Por lo menos en el caso del molibdeno, el agregado de elementos aleatorios que tienden a neutralizar estas impurezas parece ofrecer posibilidades de mejora.

ALUMINIUM FABRICATION

For Nuclear Work

By D. SLATER, B.Sc.
(*The A.P.V. Co., Ltd.*)



Using shielded welding processes high-quality joints may be made in pure aluminium. Porosity can be considerably reduced by preheating techniques, and distortion problems can be satisfactorily solved. Little is known at present of the effect of porosity in fatigue conditions. Further effort may be required to improve the already high attainable weld quality, but few applications will be found where the present high standards would be unacceptable.

ALUMINIUM, which is readily formed and welded, possesses low neutron absorption characteristics and high corrosion resistance, is a naturally suitable containing material for light or heavy water-moderated, low-pressure reactors, and has been used for this purpose on a number of occasions in this country. The overriding requirement of proof against leakage under all operating conditions and the difficulty of inspection during service render imperative the use of highly developed techniques, in order to attain the highest possible manufacturing standards.

Fabrication Requirements

Close dimensional tolerances arise from the need for containers to locate with holes in thermal and biological shielding structures, also from the requirement of exact core positioning for the highest operating efficiency. Attainment of these tolerances presents a difficult problem, especially where welds in thick sections are encountered; appropriate welding sequences have to be evolved, in order to minimize distortion.

Metallurgically, the requirement is for a vessel having 100% joint efficiency, and resistant to general and selective corrosion. Full joint efficiency, when compared with annealed plate strength, can readily be obtained in aluminium, using inert-gas-shielded welding processes, and joint strength can further be increased when some working by rolling or hammering is carried out. Aluminium weld deposits can be worked to the quarter-hard condition by rolling, and in this state it is thought that better resistance to high purity water corrosion is obtained than in the soft condition.[1] In order to induce surface hardening, soft dished ends have, in some instances, been hammer-peened, in an effort to ensure the best possible corrosion resistance.

Fabrication Problems

A major difficulty in fabricating to close dimensional tolerances is brought about by the pronounced tendency for aluminium to distort when welded, as a result of the combination of thermal stresses and high inherent plasticity. Both longitudinal and transverse shrinkage is commonly encountered in butt joints, transverse shrinkage increasing with thicknesses up to about 2½ in., above which thickness little extra shrinkage takes place.

The general effect of localized preheating is to cause distortion, due to local thermal stress and plastic strain and, therefore, steps must be taken to ensure that preheating is done in a uniform manner. Where thick sections are involved, the high thermal conductivity of aluminium can give rise to poor weld bead profile and difficulty in ensuring complete fusion in some circumstances; preheating is advisable when welding sections thicker than ½ in.

Geometrical considerations may dictate joint design, and particular care has to be taken in avoiding stress accumulation, with consequent distortion and risk of cracking, when using non-standard procedures. Care is required in handling large structures fabricated to close tolerances, as the low strength and hardness of pure aluminium renders it especially liable to mechanical damage.

The chief problem in the fabrication of aluminium, however, is its susceptibility to porosity formation in welding, and, while the effect of porosity on static tensile strength is, in the main, insignificant, little is known of its effect where fatigue or active corrosion are taking place. For this reason considerable efforts are being directed towards developing techniques for the production of pore-free weld deposits.

Fabrication Techniques

Gas welding is confined to relatively thin sections, as a high heat input rate is needed to counteract the high thermal conductivity of aluminium. The risk of corrosion resulting from flux entrapment further limits its application. It is only recently that advances in the use of inert-gas-shielded methods have made possible welds in unlimited sections of an overall quality, previously unattainable, by either gas welding or the coated electrode metal-arc process.

The quality attainable, however, appears inferior to that commonly reached in steel welding, in particular with respect to porosity formation. Both hydrogen and argon may give rise to porosity, hydrogen being formed by high temperature decomposition of hydrated alumina, dissolved in the weld pool and subsequently expelled in the form of gas bubbles at the solidification front. Argon may be entrained in certain turbulent weld pool conditions, especially at high welding currents. The pore size is influenced by weld pool solidification rate, in general increasing as the pool is cooled more slowly, while under

The illustration above is an example of manipulation to obtain downhand welding, and is the Merlin II vessel under fabrication at the A.P.V. works. (*Courtesy of AEI-John Thompson and A.W.R.E.*)

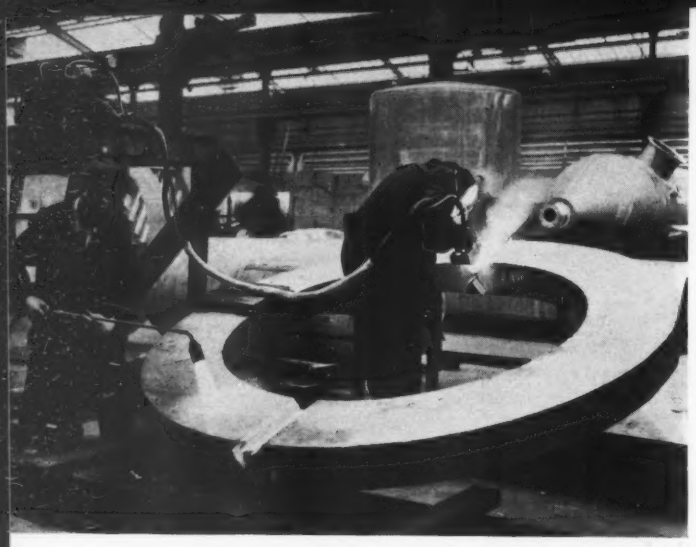


Fig. 1.—Welding pure aluminium 6 in. thick.

slow cooling conditions pore density usually decreases. Of the two inert-gas-shielded processes—namely tungsten-arc and metallic-arc—the latter is most likely to give rise to porosity, factors affecting it being high cooling rate, weld pool turbulence, and the continual introduction into the weld pool of cold wire bearing hydrated aluminium oxide and a normally unavoidable thin surface layer of worked-in dross and drawing lubricant.

Absolute cleanliness is, of course, imperative where high quality is demanded of a system so susceptible to hydrogen porosity, and the presence of either moisture or grease must be avoided, as must an excessively thick oxide film. Plate degreasing and cleaning is followed by edge preparation, which is best carried out by planing without lubrication, with a minimum of time elapsing between edge preparing and welding.

By this means a clean, grease-free, relatively unoxidized surface is available for welding, and the risk of porosity through contamination is minimized.

Welding Position

Considerable effort is usually expended in avoiding positional welding, most welds being made downhand, this not only being the most convenient mode of welding but also the one most likely to give freedom from porosity.[5] Welds made in the horizontal/vertical, overhead, and vertical-downwards positions invariably show a greater degree of porosity as compared with those made in the downhand or vertical-upwards positions. In horizontal/vertical welding porosity usually occurs on the upper side of the weld bead, suggesting a combination of gravitation effects and physical entrapment by solidifying dendrites, which factors would also account for increased porosity observed in overhead welding.

Dual-operator Welding

The inert-gas-shielded tungsten-arc process operates with considerably lower solidification rates and is, with proper precautions, generally less liable to porosity defects and, especially when the dual-operator vertical-upwards technique is used, is capable of producing virtually defect-free welds. In this technique, two operators work simultaneously, one adding filler material and the other controlling penetration, the technique requiring a high degree of skill. The operators must be used to working together if complete freedom from defects is to be achieved; in particular, lack of co-ordination can easily result in gross starting porosity and centreline oxide film inclusions, the former defect being the most difficult to avoid. Restart porosity is influenced by filler metal surface conditions, and is probably governed by local weld pool solidification rate. Initial " dwell " may also influence total gas content of the weld pool at restarts.[2]

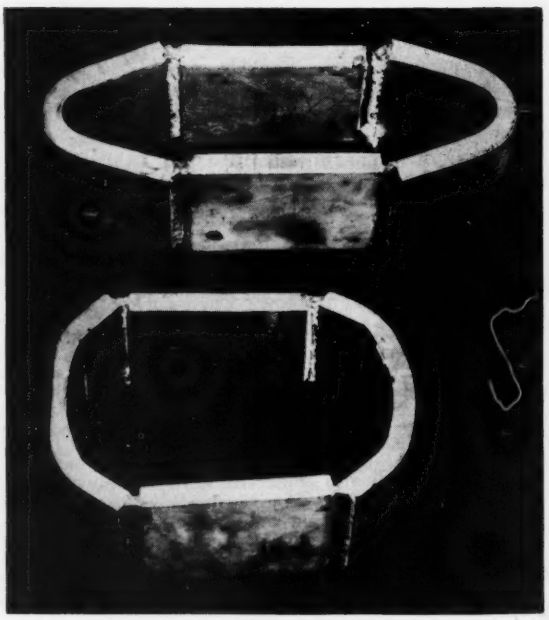
The dual-operator single-pass argonarc technique may be employed for thicknesses up to $\frac{1}{2}$ in.; the welding of greater thicknesses is attended by the risk of gross tungsten inclusions due to the high currents required. Sections in excess of $\frac{1}{2}$ in. are generally welded by the inert-gas-shielded consumable-electrode process. Apart from the inherent difficulty due to porosity formation, already discussed, this process suffers from the additional disadvantage that, owing to the high thermal conductivity of pure aluminium, weld deposits laid on cold plate tend to be upstanding in form and, in some instances, this may lead to serious lack of side fusion when making multi-pass welds. To overcome this difficulty it is necessary to preheat when welding thick sections, the degree of preheat being governed by joint configuration and distortion considerations.

Preheating

Of the preheating methods available, the two most commonly used are electrical resistance heating mats and oxy-propane or oxy-coal gas torches, the former method being used where grossly unequal sections have to be joined, distortion minimized, or where disturbance of the shielding gas is inadmissible as in dual-operator argonarc welding. Heat input rates are low but, provided that adequate insulation is possible to reduce heat losses and sufficient time is allowed to ensure temperature stabilization, completely uniform preheating can be achieved with excellent results on weld quality. Temperature control is readily maintained, and for critical work, where the interplay between welding speed and current, and degree of preheating are of prime importance in achieving controlled penetration, the electric blanket forms the most useful method of preheating.

Oxy-propane torches find their greatest application where insufficient time is available for blanket preheating.

Fig. 2.—Procedure test pieces for corner welds.



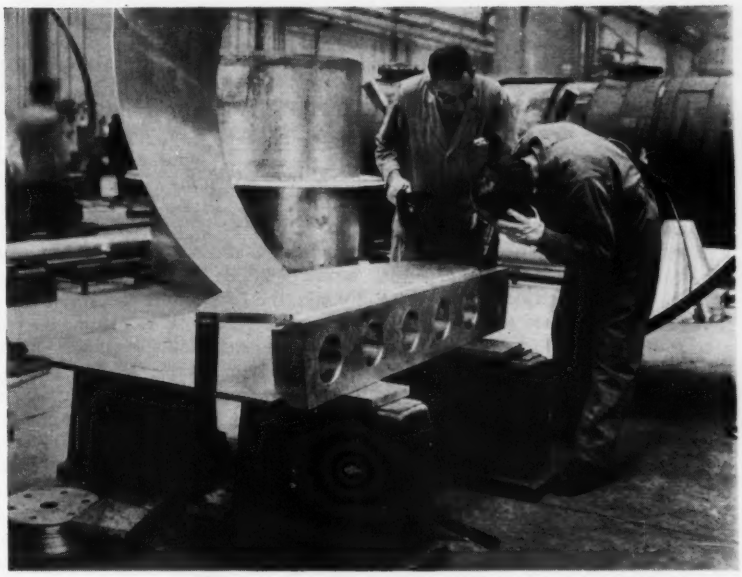


Fig. 4.—Procedure test to check joint and component distortion in welding.

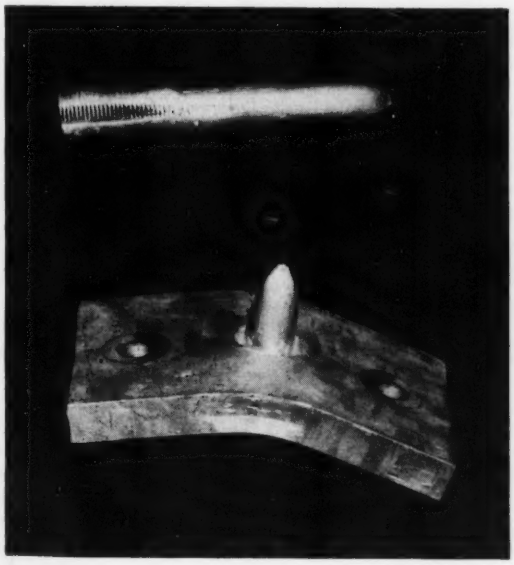
or where local preheating is required from one side while welding proceeds from the other, as in fully automatic multi-pass circumferential seam welding. In this case preheating precedes welding by only a small interval—about 30 seconds—the torch size and set-up being chosen in relation to section thickness and welding speed to give the required degree of preheat at the point of welding, while at the same time avoiding local "burning." "Burning" is particularly easy when using a high intensity oxy-propane torch on aluminium which, at its melting point, 660°C, is barely at red heat. Operators should therefore use the torches no closer than 12 in. to the work. In the manual application of preheat particular care is needed to position and direct the torches so as to cause the minimum thermal distortion of the work, and the degree of preheating must be controlled within a specified range by means of temperature-indicating crayons, in order that weld shrinkage may be as calculated. This control is particularly important for thicknesses above 1 in. where the highest dimensional accuracy is required.

Porosity

It is found that preheating tends to cause agglomeration of fine dispersed porosity, resulting in increased pore size but lower pore density with moderate preheat temperatures. Almost complete freedom from porosity, but with the risk of an occasional gross pore, may be obtained by employing temperatures in the region of 300°C, and therefore careful control is necessary when preheating either for welding or rectification, but particularly in the latter case.

When making double-sided welds in heavy sections by the inert-gas-shielded consumable-electrode process, it is usual to build up the first side on a substantial root face, subsequently back chipping before filling the second side. This practice can lead to the formation of linear porosity at the bottom of the root run on the first side,[3] the effects of which may not be completely removed by back chipping. This difficulty can be overcome by reducing the root face and using the dual-operator vertical argonarc technique to make the root run, root defects and back chipping being eliminated. Where suitable preheating is employed, this technique is satisfactory for thicknesses up to 3 in. Distortion and possible cracking are avoided if adequate handling facilities are available to permit subsequent runs to be made in a symmetrical manner, due attention being paid to joint strength at all stages of fabrication. Welding of a 6-in. thick section in 99.5% aluminium is illustrated in Fig. 1, showing symmetrical weld metal deposition.

Fig. 3.—Procedure test pieces for stub joint.



Fabrication to the standards required for nuclear energy purposes necessarily involves the question of rectification, as it is seldom possible to weld long seams manually with complete freedom from defects. Skilled operators will normally produce welds free of oxide film inclusions, cracks, or lack of fusion, but, should these occur, repair could be effected. Restart porosity more easily occurs, and its rectification in many instances may not be practicable or even desirable. It is commonly found that, where the weld contains fine pores at restarts and is saturated with gas, attempts at rectification, necessarily involving a restart, usually meet with limited success. The residual porosity tends on the whole to increase in size. Where adequate preheating and cleaning methods are used, however, gross pores may be removed, but pores of $\frac{1}{16}$ in. diameter or smaller are best left alone.

Quality Control

The danger of copper contamination resulting in accelerated corrosion[4] leads to extensive analytical control of materials used in the construction of aluminium reactor tanks. Whether aluminium of 99.8% or 99.5% purity is used, the copper content is specially maintained below a maximum content of 0.01%. This applies to filler materials used in welding, and special arrangements are made to bond these materials for use, after analytical checks have been made, on specific projects only. All materials are bonded by Inspection and issued only on Inspection

authority after the necessary laboratory test reports have been obtained. Welding procedures for butt joints can be simply specified, but where unusual configurations are encountered full-scale procedure tests are carried out. Such procedure test pieces are shown in Figs. 2, 3 and 4. Test pieces are radiographed and sectioned to ensure that full fusion has taken place and that weld quality is satisfactory. At the same time, useful checks on joint shrinkage and component distortion are taken, and alterations to plate and joint sizes made where necessary.

Procedures having been established, no welder is allowed to commence work until satisfactory welder qualification tests have been obtained. These usually take the form of butt joint test pieces simulating the thicknesses, positions and processes obtaining in fabrication. A convenient fillet weld test piece consists of an inclined 6 in. diameter tube passing through plate at an angle of 60°, subsequent sectioning affording checks on both obtuse and acute angle fillets. After radiography, tensile and bend pieces are machined from the butt weld test coupons and joint efficiency evaluated on the basis of the strength of annealed plate, a joint efficiency of 100% being required.

Examination and Testing

During fabrication, radiographic inspection is supplemented by mechanical tests on coupon plates attached to longitudinal seams, or other seams meriting special attention. In addition, as radiography cannot be relied upon to detect microfissuring, welds are checked for cracks, using penetrant dye which may be of either the red staining or fluorescent form. The former is preferred, as viewing of the fluorescent penetrant is by ultra-violet radiation and is, on the whole, inconvenient in an open shop. Microfissuring of the weld surface is occasionally encountered when fabricating 99.8% pure aluminium, but is seldom found with 99.5% material owing to its higher impurity level and consequent greater resistance to hot-shortness.[2]

Careful attention is paid to details of radiographic technique necessary to achieve maximum flaw detection sensitivity. A minimum sensitivity of 2% is usually required, as measured by step wedge or other penetrameters; thus, a pore of $\frac{1}{16}$ in. diameter would just be visible in a 3-in. section.

Ultrasonic inspection is used to check tubes, forgings and plate for laminations and possible cracks, but is seldom used for weld evaluation where radiography is being carried out. This is probably largely a matter of ease of interpretation combined with the requirement of a permanent record, which can most readily be obtained by radiographic methods.

The dimensional accuracy required in reactor work is such that special measuring techniques are invariably used. The probable dimensional effects of welding are assessed, and fabrication proceeds accordingly, accuracy being attained by means of optically-located master jig plates.

Cleaning is carried out on completion, using caustic soda and nitric acid solutions of controlled composition, vessels where possible being partially filled and rotated on trunnions to ensure a final smooth matt even surface.

Acknowledgment

The author wishes to thank the directors of The A.P.V. Co., Ltd., for permission to publish this article.

REFERENCES

1. Huddle, A. H. and Wilkins, N. J. M. The Corrosion of Commercially Available Pure Aluminium in Demineralised Water between 125° and 300°C. A.E.R.E. M/R 1669, May, 1955.
2. Lancaster, J. F. The Welding of Aluminium Tanks for Experimental Reactors. *Brit. Welding J.*, Aug., 1957, p. 354–360.
3. Wilson, E. M. Practical Application of Inert-Gas Metal-Arc Welding to Some Aluminium Alloys. *Welding and Metal Fabrication*, Dec., 1957.
4. Botham, G. H. and Bryson, W. R. Note on the Corrosion of Aluminium Dairy Equipment by Water. *J. Dai. Res.*, **20** (2), June, 1953, p. 154–155.

La Fabrication de l'Aluminium pour les Besoins de l'Energie Nucléaire

L'expérience a démontré que lors de l'emploi des nouveaux procédés de soudure à écran de gaz inertes des joints de haute qualité pourront être effectués en aluminium pur. La porosité constitute le défaut qui a le plus de chances de se présenter en soudure à arc métallique à gaz inerte et à cet égard la qualité des soudures en aluminium semblerait être plutôt inférieure à celle qui s'obtient généralement dans la soudure acier. La porosité pourra être considérablement réduite en employant des techniques de préchauffage appropriées et, pourvu qu'une expérience suffisante ait été acquise dans l'emploi des chalumeaux de préchauffage au propane, alors les problèmes de distorsion que l'on rencontre inévitablement pourront être résolus de manière satisfaisante. Dans la tension statique la porosité ne joue aucun rôle significatif, et une efficacité de joint de 100% pourra facilement être obtenue. On ne sait que peu de choses à l'heure actuelle sur l'effet de la porosité dans les conditions de fatigue ou là où une tolérance de corrosion est donnée et une corrosion active se produit. Il est possible que des efforts supplémentaires soient requis pour améliorer la qualité de soudure déjà élevée pouvant être atteinte et pour établir les effets précis de tous défauts qui semblent appartenir à la nature même des procédés de soudure. Il est peu probable, toutefois, qu'il soit trouvé un grand nombre d'applications où les normes élevées actuelles ne soient pas acceptables.

Konstruktionen aus Aluminium in Atom-Kraftwerken

Erfahrung hat gezeigt, dass ausgezeichnete Verbände mit reinem Aluminium mittels der neuen Schweissverfahren in neutraler Atmosphäre hergestellt werden können. Porosität ist der Fehler, der beim Metall-Schweissen im Lichtbogen am wahrscheinlichsten ist, und deshalb könnte in dieser Hinsicht die Qualität der Aluminium-Schweisstellen derjenigen, die beim Schweissen von Stahl erreichbar ist, etwas unterlegen erscheinen. Die Porosität kann erheblich reduziert werden, wenn man eine geeignete Erwärmungstechnik anwendet, und wenn man genügend Erfahrungen im Gebrauch von Propan-Brennern zum Vorwärmen gesammelt hat, worauf dann das Problem der Verzerrungen, auf das man ganz sicher stösst, zufriedenstellend gelöst werden kann. Bei statischer Spannung spielt Porosität keine bedeutende Rolle, sodass man dann eine 100-prozentige Sicherheit für den Verband erhalten kann. Bisher weiss man jedoch wenig über die Wirkung von Porosität unter Bedingungen, die zu Ermüdungserscheinungen führen, oder wo man mit Korrosion rechnet und diese in der Tat auftritt. Es ist möglich, dass weitere Arbeit notwendig wird, um die bereits recht hohe Qualität der Schweissung, die man erreicht hat, weiter zu verbessern und genau festzustellen, welche Wirkung solche Fehler haben, die mit Schweissverfahren stets verknüpft zu sein scheinen. Es ist indessen unwahrscheinlich, dass man viele Anwendungen finden wird, wo der gegenwärtige bereits sehr hohe Standard nicht annehmbar sein sollte.

Fabricacion de Aluminio para Fines de Energia Nuclear

La experiencia ha demostrado que mediante el empleo del nuevo proceso de soldadura protegida al gas inerte se pueden conseguir uniones de alta calidad en el aluminio puro. La porosidad constituye el defecto más saliente en la soldadura metálica al arco por gas inerte y a este respecto la calidad de las soldaduras hechas en el aluminio pudieran parecer un tanto inferiores a las que generalmente se consiguen en la soldadura del acero. La porosidad puede ser considerablemente reducida por medio de las técnicas adecuadas de precalentamiento y, siempre que se hava adquirido la experiencia adecuada en el empleo de sopletes precalentadores al propano. los problemas de distorsión ue inevitablemente se encuentran, pueden ser solucionados satisfactoriamente. En la tensión estática la porosidad no juega un papel significativo, y puede lograrse fácilmente una eficiencia de junta del 100%. Poco se conoce hasta ahora del efecto de la porosidad en condiciones de fatiga o donde se da una tolerancia de corrosión y la corrosión activa está ocurriendo. Es muy posible que se hagan necesarios mayores esfuerzos para mejorar la ya alta calidad de soldadura lograble y en el establecimiento de los efectos precisos de aquellos defectos que parecen inherentes en el proceso de soldadura. Sin embargo, es improbable que se encuentren muchas aplicaciones en las cuales los altos niveles actuales resulten inaceptables.

NEUTRON DETECTORS—

A Survey

By J. SHARPE, B.Sc., A.M.I.E.E.
(Chief Engineer, EMI Electronics, Ltd.)

A general survey of radiation detectors presented in *Nuclear Engineering* in May, 1957, included a necessarily contracted account of instruments specifically adapted for work with neutrons. Utilizing this survey as a basis, it is now proposed to deal somewhat more completely with this aspect of the field.

THE importance of the neutron in the operation of nuclear reactors, and the enormous fluxes which are generated, necessitate instruments both for engineering control and for health physics. Research in this field and in other branches of nuclear physics often needs more complicated devices which can give a rapid evaluation of the energy spectrum of a neutron flux.

Measurement is complicated by three factors:—

1. Neutrons are uncharged particles and so cannot be detected until they have interacted with some reactive element to produce a charged particle which can excite a detection medium, as explained [1] in a previous article. The types of reaction used, and the methods of use, are illustrated in Figs. 1 and 2 and Table 1.

2. Neutrons nearly always occur in conjunction with gamma rays, of comparable, or greater, energy flux, and many detectors give a rather similar response to the two types of radiation, so the specific detection of neutrons is made difficult.

3. Multiple scattering of fast neutrons causes rapid degradation in energy, so there is often an accompanying flux of thermalized neutrons. Since many of the more useful reactive elements have much higher cross-sections for thermal than for fast neutrons, this factor introduces complications. This is illustrated by Fig. 3, which shows the reactive cross-section for many elements as a function of neutron energy.

From these, it will be seen that instruments for thermal neutrons are, in general, easier to design and operate than those for fast neutrons, while intermediate energies between 10 and 10^5 eV will be very difficult to deal with.

THERMAL NEUTRONS

Neutrons in thermal equilibrium with matter at 20°C are distributed in energy around 0.025 eV, corresponding to a mean velocity of 2,200 m/sec. At this energy, the cross-section of the (n, α) reaction in B^{10} is 3,770 barns. In view of its generally useful nature, the design of detectors for thermal neutrons will be first discussed in terms of boron.

In common with other slow neutron interactions remote from a resonance, the cross-section, σ, of B^{10} (n, α) varies inversely with neutron velocity (the so-called $1/v$ law); a B^{10} detector exposed to a flux of neutrons distributed in velocity will then give a reading proportional to the neutron density in that region, unless the sink effect of the B^{10} absorption be sufficient to cause appreciable perturbation of density.

Boron Trifluoride Detectors

The most sensitive slow neutron detector in general use is a $B^{10}F_3$ filled proportional counter.[2] The 2.5 MeV available as kinetic energy of the alpha particle and Li^7 nucleus ionizes the BF_3 gas, and the pulse of ionization may be

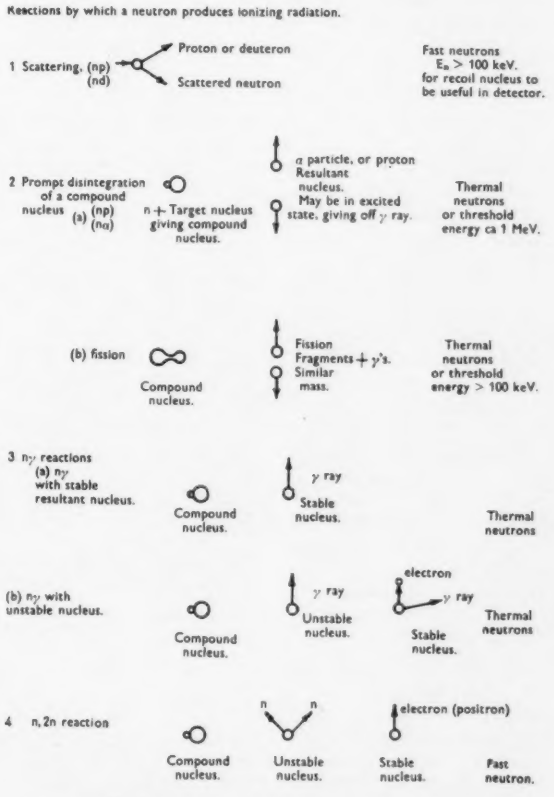

Reactions by which a neutron produces ionizing radiation.
1 Scattering, (np) (nd)
Proton or deuteron
Scattered neutron
Fast neutrons $E_n > 100$ keV. for recoil nucleus to be useful in detector.
2 Prompt disintegration of a compound nucleus (a) (np) (nα)
n + Target nucleus giving compound nucleus.
α particle, or proton Resultant nucleus.
May be in excited state, giving off γ ray.
Thermal neutrons or threshold energy ca 1 MeV.
(b) fission
Compound nucleus.
Fission Fragments + γ's. Similar mass.
Thermal neutrons or threshold energy > 100 keV.
3 nγ reactions
(a) nγ with stable resultant nucleus.
Compound nucleus.
γ ray
Stable nucleus.
Thermal neutrons
(b) nγ with unstable nucleus.
Compound nucleus.
γ ray
Unstable nucleus.
electron
γ ray
Stable nucleus.
Thermal neutrons
4 n, 2n reaction
Compound nucleus.
n n
Unstable nucleus.
electron (positron)
Stable nucleus.
Fast neutron.

Fig. 1.—Four types of reaction by which neutrons produce ionizing radiations.

amplified by the process of gas multiplication at the anode wire to give a signal of ca 50 mV into 25 pf. Great care in construction of the counter tubes and in purification of the gas filling enables the inherently good energy resolution of a proportional counter to be realized in BF_3 tubes, so that extremely flat voltage plateaux are obtained.

Such counters are obtainable in diameters from 1 to 5 cm, and in lengths from 2 to 100 cm, filled at pressures up to 150 cm Hg with both natural BF_3 and enriched material containing 96% B^{10}. The sensitivity obtainable from a rather typical tube, of i.d. 2.2 cm, active length 15 cm, filled with 40 cm Hg of 96% $B^{10}F_3$, is 2 counts/neutron, cm^2 for thermal neutrons; the background count rate of a tube of this type is such that the very low flux of 0.01 n/cm^2, sec is measurable, providing the ambient gamma-ray flux is not more than a few r/h. In a very high gamma flux, pile-up in the proportional counter gives rise to spurious counts, and a limit is reached for practical operation at about 100 r/h.

A BF_3 counter moved from a low to a high neutron flux is affected by the *change* in space charge of the electron avalanche at the central wire, which causes a shift of the plateau. For practical purposes, these counters cannot be used in thermal neutron fluxes greater than between 10^4 and 10^5 n/cm^2, sec.

Ionization Chambers

An ionization chamber, designed to accept a sufficiently high saturation voltage, is not subject to this limitation, and a typical instrument designed for reactor control,[3] having a sensitive volume of 180 cm^3 filled to 30 cm Hg with $B^{10}F_3$, will operate up to neutron fluxes of 3×10^9 n/cm^2, sec, giving an ion current of 10^{-4} amp. The lower useful limit of current is 10^{-12} amp, corresponding to 30 n/cm^2, sec. Unfortunately, the low discrimination of an ion chamber against gammas prevents its simultaneous use in a low neutron, and high gamma ray, flux, the above limiting currents corresponding to gamma intensities of 10^7 r/h and 0.1 r/h, respectively.

In a similar chamber, lined internally with 500 mg of natural boron and filled with 15 cm Hg of hydrogen, the range of gamma-ray sensitivity is unchanged, but the operating neutron flux is 10^3 to 10^{11} n/cm^2, sec.

Direct measurement of still higher fluxes is complicated by the rapid activation of the materials of construction of the ion chamber, giving spurious readings due to the beta and gamma radiation produced, and also by poor performance of insulators. Recourse may now be had to thermal detectors, which, for instance, take the form of boron-coated junctions in an array of chromel - alumel thermocouples,[4] giving an output of tens of millivolts at 10^{12} n/cm^2, sec, with a time constant of 13 sec. A simpler assembly, with a time constant of 40 sec, consists of alternate discs of mild steel and 2% boron steel, linked with iron and constantan strips.[4]. A more recently described arrangement,[5] with a time constant of 37 m/sec, uses 100 sets of bismuth-boron impregnated copper-lead discs.

A disadvantage of the simple thermopiles described above is an appreciable temperature coefficient, since their output may be halved as the ambient temperature rises from 50 to 350°C. In order to get over this difficulty a servo system has been described,[6] which maintains two almost identical ceramic elements at a constant temperature. One of these elements is neutron sensitive and the other contains a small electrical heater, the input power of which is adjusted to balance out the power dissipation due to neutron absorption in the other element. For 2% by weight of B^{10}, a flux range of 10^{14} to 10^{15} n/cm^2, sec could be measured, although in the actual instrument described, enriched uranium was used, giving a range of 10^{13} to 10^{14}, at ambient temperatures up to 350°C.

Other Materials

In the detectors described above, other materials could be used in place of B^{10}, where physical form allowed. For instance, He^3 could be used in a proportional counter, but this is so scarce that in practice its use is restricted to rather special applications (see below). The main advantage of replacing solid boron by a lithium compound would be a reduction in depletion rate, which is proportional to cross-section, but this would be achieved at the cost of a reduction to one half of the power available. On the other hand, lithium is available in a high-efficiency phosphor, as boron is not, and LiI activated by thallium or europium gives large scintillations from the (n, α) reaction in Li^6. It is also extremely efficient for gamma rays, however, and

TABLE 1
Neutron Reactions

Target Nucleus	Isotopic %	Reaction	Threshold MeV	Thermal Neutron cross section. σ, barns	Comments
H^1	99.984	n, γ	—	0.32	Used as gas, or hydrogenous phosphor or radiator.
H^2	0.0156	n, γ	—	0.00092	
He^3	1.3×10^{-4} (Atmospheric)	n, p $\rightarrow$ H^3 + 0.78 MeV	—	5,000	Used as gas.
Li^6	7.30	n, α $\rightarrow$ H^3+4.80 MeV	—	902	Used as LiF foil, or LiI phosphor.
Li^7	92.70	n, γ $\rightarrow$ 88 sec Li^8	—	0.033	
B^{10}	18.83	1. n, α $\rightarrow$ Li^7+2.78 MeV 2. n, α $\rightarrow$ Li^{7*}+2.34 MeV Li^{7*} $\rightarrow$ Li^7+0.44 MeVγ	—	3,770	σ_1/σ_2 (thermal)=0.075. Used as B foil, B_2O_3, BF_3, borate in phosphors.
B^{11}	81.17	n, γ $\rightarrow$ 0.027 sec B^{12}	—	0.05	
N^{14}	99.63	n, p $\rightarrow$ C^{14} + 0.628 MeV n, α $\rightarrow$ B^{11}	— 0.3	1.75 —	Used as gas.
C^{12}	98.89	n, 2n $\rightarrow$ 20 min C^{11}	20.4	—	Used as C foil, anthracene phosphor.
S^{32}	95.06	n, p $\rightarrow$ 14.3 d P^{32} n, α $\rightarrow$ Stable Si^{29}	1.0 1.16	— —	Used as ZnS–Ag.
Mn^{55}	100	n, γ $\rightarrow$ 2.6 h Mn^{56}	—	13	Used as foil, or $MnSO_4$ solution.
Cd^{113}	12.34	n, γ $\rightarrow$ Stable Cd^{114}	—	20,000	Used as foil, or in liquid phosphor.
In^{115}	95.84	n, γ $\rightarrow$ 54 min In^{116} n, γ $\rightarrow$ 13 sec In^{116}	— —	145 52	Used as foil, resonances at 1.4, 3.8 and 9 eV.
Gd^{155}	14.78	n, γ $\rightarrow$ Stable Gd^{156} and Gd^{158}	—	69,000	Natural element has thermal σ of 37,000 barns.
Gd^{157}	15.71		—	Pile n. 240,000	
Bi^{209}	100	Fission.	20	—	
Th^{232}	100	Fission.	1.1	—	
U^{235}	0.71	Fission.	—	545	Competitive capture σ (thermal)=101 barns.
U^{238}	99.28	Fission.	1.0	—	σ (thermal)=3.5 barns.
Np^{237}	—	Fission.	0.1	—	

prolonged exposure to neutrons may activate the iodine by an (n, γ) reaction of 6.8 barns, to give 25 min I^{128}, having a 2 MeV beta. The extreme deliquescence of the material is its biggest drawback, and makes it difficult to prepare and use.

Solid B^{10} can often with advantage be replaced by a fissile material, such as U^{235}, where the very high energy available from fission is needed and where the specific response to a particular neutron spectrum is necessary. Fission counters containing various amounts of U^{235}, from 0.04 to 3,000 mg, have sensitivities from 3×10^{-5} to 1.7 counts/n, cm^2, and may be used in maximum neutron fluxes between 10^{10} and 10^5 n/cm^2, sec, and gamma-ray fluxes of the order of 10^5 r/h.[7]

The instruments described above utilize prompt charged particles produced by the neutron reaction. In some reactions the product nucleus is left in an excited state, which decays very rapidly (10^{-8} sec), by gamma emission, as is the case with

$$B^{10}\ (n, \alpha) \rightarrow Li^{7*} \rightarrow Li^7 + \gamma$$

while in (n, γ) reactions a multiplicity of gamma rays is emitted. In either case, the gamma radiation may be detected with a scintillation counter as single events,[8] or as coincidences.[9] This type of detector can give a uniform sensitivity over the energy range to which the neutron absorber is "black," and is particularly useful when the time of occurrence is known, as in a time of flight instrument.

Where an (n, γ) reaction results in a radioactive isotope, the induced activity resulting from a timed exposure may be assayed in a beta or gamma counter, and after correction for radioactive decay, may be used to calculate the neutron flux. In, Mn, Au and Co are commonly used for this purpose, and the technique is generally employed for the determination of neutron density in sub-critical and low-power reactors, where several hundred foils may be exposed simultaneously. Some materials used in this way, e.g. In, have resonances in the epithermal region, between 0.1 and 10 eV, and these may be used, in conjunction with Cd shields, to screen off thermal neutrons, to gain information about the neutron spectrum in this energy region.

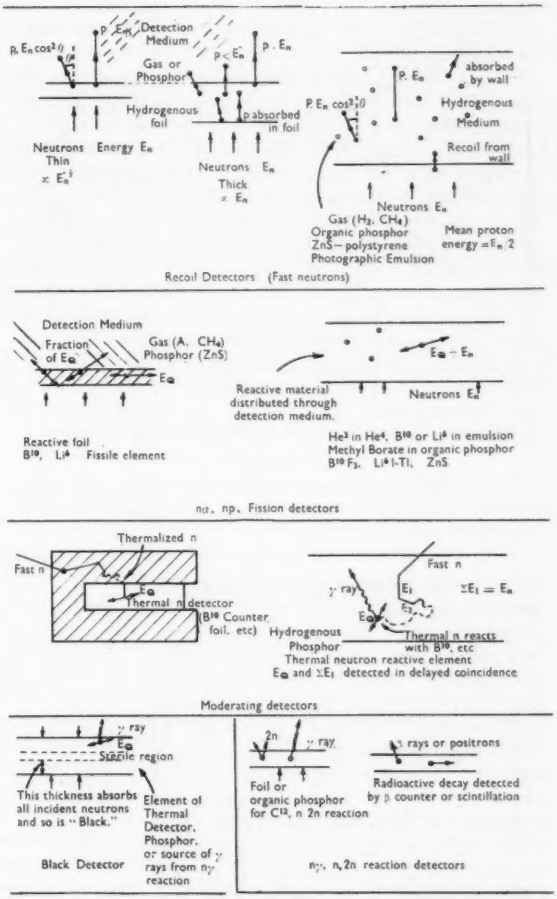


Fig. 2.—Operating principles of various types of detector.

FAST NEUTRONS

In contrast with the slow neutron detectors dealt with above, which operate effectively between 0.01 and 10 eV, neutron energies over a much wider range may be encountered in the fast-neutron field. Two requirements may be distinguished here according to whether a simple measurement of flux, independent of energy, or the more complicated determination of a spectrum, is needed.

Long Counter

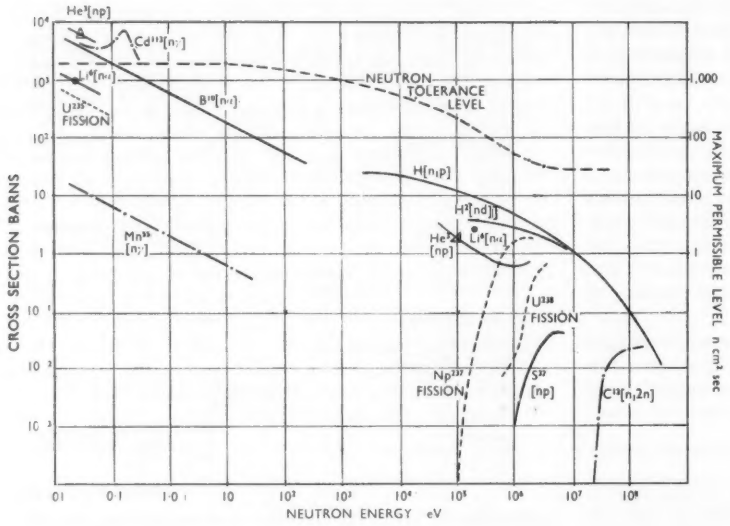
Since the reaction cross-section varies with neutron energy so markedly (Fig. 3), it is fairly obvious that an instrument which is to measure flux independently of energy will be a contrived, rather than a fundamental, device. One example is the "Long Counter"[10] shown in Fig. 4, in which the detector proper is a BF_3 counter surrounded by a moderator to thermalize fast neutrons, which is, in turn, surrounded by a B_2O_3 shield to minimize side sensitivity. The moderator is empirically adjusted by drilling holes in the front face to flatten the response, which (typically) is fairly uniform from 25 keV to 5 MeV, falling off by a factor of about two down to thermal energies. With a suitable BF_3 counter, an efficiency of about 10^{-5} is obtained for a point source of neutrons mounted 100 cm from the front face. Simplified versions of this device are used in portable fast-neutron detectors.

Wax Castles

A similar arrangement giving a rather higher efficiency with an internal source is the wax castle in Fig. 4b. Here, six $B^{10}F_3$ counters spaced equally around a PCD of $11\frac{1}{2}$ in. give a detection efficiency of 1% for a source in the central cavity, reasonably independent of energy over the range 20 keV to 5 MeV.

A variation of this general type of counter is shown in Fig. 4c, and may be used to gain some information about the neutron spectrum. The slow counter, nearest to the source has a maximum response for thermal neutrons, which falls off slowly for energies up to 200 keV, then more rapidly, while the modified long counter has low response at thermal energies, rising fairly rapidly to 200 keV, then rising more slowly as the energy increases to 3 MeV.[11] The different counting rates in the two detectors when exposed to the same beam of neutrons give some idea of the mean energy of the radiation.

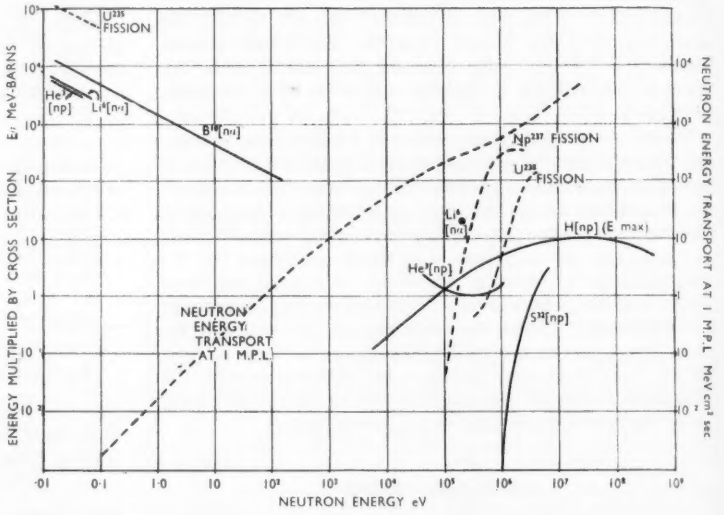
The long counter of Fig. 4a and the wax castle in Fig. 4b can obviously be used to calibrate neutron sources, once the efficiency has been determined, and this requires a method for absolute calibration of a suitable standard neutron source, and some means of comparing this standard with other, substandard, sources, perhaps of different



(Left) Fig. 3a.—Neutron reaction cross-sections for various elements as a function of neutron energy.

(Below) Fig. 3b.—Energy transport and energy × cross section for various elements as a function of neutron energy.

(Right) Fig. 4.—Fast neutron counters using moderator and boron trifluoride detector.

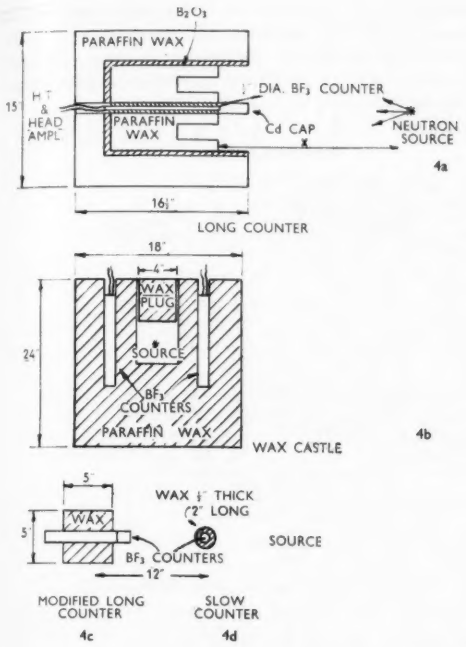


energy. The most accurate method for absolute calibration is the "swing" method, in which the change in reactivity of a nuclear pile is measured as the source is inserted,[12] while sources may be accurately compared by the manganese bath method.[13] A large (36 in. dia × 36 in. high) bath of manganese sulphate solution in water, containing 600 g $MnSO_4.5H_2O$ per litre, is sufficiently extensive to thermalize and capture (to form Mn^{56}) all the neutrons produced from a source suspended at its centre. After exposure for a standard time, the source is removed, the bath well stirred, and the activity measured by some convenient instrument, such as a scintillation gamma counter. After correction for decay, and time of exposure, the bath activity is proportional to the source intensity.

The process of thermalization in a hydrogenous moderator is carried out by the successive dissipation of the neutron energy among recoil nuclei, the majority of which are protons. If the moderator is, in fact, a transparent organic phosphor, the scintillations produced by the recoil nuclei can be observed by a photomultiplier and used to measure the neutron energy. Owing to the variation in phosphor efficiency with particle mass and energy, and the fact that monoenergetic neutrons may, in the process of energy loss, produce protons over a wide range of energy, an appreciable spread in light output is observed. It has been shown, for example, that 14 MeV neutrons completely scattered in a particular phosphor would produce a pulse distribution with a width of 10% at half maximum.[14] Unfortunately, the electron produced by a scattered gamma ray in an organic phosphor gives between three and five times the light output of a proton of comparable energy, so it is necessary to find some way of identifying those pulses due to neutrons. One method[15] utilizes the thermalized neutron, which is the end product of the scattered fast neutron, by incorporating up to 50% of methyl borate in a terphenyl-phenylcyclohexane liquid phosphor. Capture of the thermal neutron with an (n, α) reaction in B^{10} occurs about 2 μsec after the initial recoil, and this gives a pulse of about 30 photoelectrons which is used in a delayed coincidence circuit to identify its precursor. In place of boron, a cadmium compound has been used[16] from which the gamma ray from the (n, γ) capture is observed.

Gamma Proton Discrimination

The above technique provides a way of distinguishing gamma-ray pulses from proton pulses, at the expense of reduced efficiency of phosphor (due to the diluting inclusion) and rather complex circuitry. Very recently, a powerful new technique has been developed at A.E.R.E. which turns on the fact that scintillations produced in many organic phosphors, stilbene being a good example, have differing decay times, depending on the nature of the exciting charged particle.[17] An elegant method of utilizing this effect to distinguish between electron and proton pulses gives the promise of neutron detectors of 20 to 50% efficiency, with a gamma-ray efficiency reduced to 0.1%, for neutrons of energy above 500 keV.[18] Perhaps the most intriguing aspect of the recent work is the fact that the



difference does not lie in the fast component of the decay, with a time constant of 5 μsec, but in the slower (100 μsec) component,[19] so that the technique does not demand very fast photomultiplier tubes and, in fact, the Harwell work has been done with EMI venetian-blind photomultipliers run under conditions giving output currents around 50 mA.

The poor discrimination given by a simple organic phosphor against gamma rays is due to the use of a uniform phosphor which is much larger than is necessary to absorb the energy of a recoil proton, and so provides adequate stopping power for fast electrons. Where only the roughest indication of neutron energy is needed, no attempt need be made to ensure complete scattering of the neutron, and a phosphor operating on the first recoil proton can be used, discrimination against gammas being obtained by separation of the hydrogenous scattering medium from the (inorganic) phosphor. Fragments of KI-Tl dispersed in a hydrocarbon of approximately comparable refractive index,[20] and ZnS-Ag distributed in a plastic disc,[21] have been used. The optimum design for this latter is 1.5 g ZnS-Ag mixed with 10 g Perspex, compressed into a button about 1 cm thick. The very considerable light scattering in this material gives a wide range of pulse amplitudes, so the detection efficiency depends very much on the bias level used, and can be about 1% for 5 MeV neutrons. The gamma discrimination also depends on the bias level, and operation in a gamma flux of about 1 r/h is possible. More recently,[22] this type of detector has been turned inside out by distributing small spheres of plastic phosphor, equal in diameter to the range of a recoil proton, through a non-hydrogenous liquid ($Cl_3F_3C_6$).

Further separation of scattering material and detection medium can be achieved by mounting a thick hydrogenous radiator close to a ZnS-Ag screen. As shown in Fig. 2, protons of all energy emerge from the radiator, and if all of these can be detected it can be shown[23] that the rate of production is proportional to the incident neutron energy flux. An instrument for fast neutron detection using a hollow spherical plastic radiator 7 in. in dia, coated internally with ZnS-Ag, and viewed by a PM tube through an open cap, gives a count rate of 10 counts/sec, for an incident flux of 150 MeV/cm², sec, with a bias level set to reject counts from 0.1 r/h of gamma rays.[24]

When a thin hydrogenous radiator is mounted normally to a flux of neutrons of energy E_n, the recoil protons emerging normal to the radiator have energy E_n (Fig. 2), and by collimation these can be selected for range measurement[25] or can be absorbed in the gas of a proportional counter,[26] and by this means the neutron spectrum can be deduced. A polythene foil 100 μg/cm² thick will emit one recoil proton per 10^5 neutrons of 1 MeV energy. (The infinitely thick radiator of ref. 24 gives 1 proton/5,000 1 MeV neutrons.)

In place of a radiator, the rectangular spectrum of recoil protons from monoenergetic neutrons can be produced and observed in a proportional counter[27] or ion chamber[28] filled with a hydrogenous gas such as CH_4. The superposition of rectangular distributions given by a complex spectrum are, however, difficult to interpret.

Instead of observing ion pulses from a chamber filled with H_2 or CH_4, the mean current produced can be used to give a measure of a fast neutron flux of constant energy spectrum. A 5-litre ion chamber used by the U.K.A.E.A.[28] gives a current of 3×10^{-12} amp when exposed to a flux of 60 n/cm², sec of 1 MeV energy, when filled to 20 atm with H_2. In a flux of gamma rays of 0.01 r/h a current of 7×10^{-12} amp is observed, so the chamber is less sensitive to 1 m.p.l. of neutrons than to 1 m.p.l. of gamma rays. Some correction for this unwanted sensitivity may be achieved by a separate gamma measurement in a similar chamber filled with ca 2 atm of Argon, which has almost identical gamma-ray response, at least for radium gamma rays.

The differing atomic number of the gas filling in the two ion chambers just described precludes identical gamma-ray response over a wide range of energies. A better approximation has been achieved by using two identical chambers filled with ethylene, C_2H_4, and deuterated ethylene, C_2D_4, respectively.[29] Since the electron density is the same in each case, the chambers will have exactly similar sensitivity to gamma rays of any energy, while the neutron responses will differ both by virtue of the lower neutron collision cross-section with deuterons as compared with protons (Fig. 3), and by the 12% reduction in recoil energy, due to the greater mass of the deuteron. Calculations of neutron flux from the observed ion currents in the two chambers must take account of the non-isotropic nature of the (n, d) scattering. A scintillation analogue of this differential measurement uses two phosphors of identical electron density but greatly different proton density.[30]

While the methods just described give information about the neutron energy flux, their responses are not weighted to take account of the dose delivered to tissue, which is assumed to contain 10.1% H_2 and 3.5% N_2. As will be seen from Fig. 3, the maximum permissible level for neutrons varies from 30/cm², sec above 3 MeV, to 200/cm², sec at 0.1 MeV, to 2,000/cm², sec below 10 eV. Apart from various attempts to make tissue equivalent ion chambers,[31] corrected for gamma sensitivity by one of the methods described above, the most promising type of instrument for health physics work appears to be a proportional counter lined with polythene and filled with CH_4. Empirical adjustment of the area of polythene and the gas filling pressure enables the counting sensitivity to be adjusted closely to the inverse of the m.p.l. vs. energy curve, over the range 0.1 to 15 MeV. The great advantage

of this device is its low sensitivity to gamma rays, a dose discrimination of 1,000 : 1 being obtained.[32]

The above discussion of fast neutron detection has been confined to (n, p) interactions with hydrogen. Other reactions may also be used, based on the equation:

Neutron (Energy E_n) $+A$=Charged particles$+E_n+(Q)$. For elements, A, reacting with thermal neutrons, Q is positive, e.g. 0.78 MeV for He^3 (n, p). A negative value of Q implies a threshold energy, below which reaction does not occur.

A proportional counter containing He^3 has been used to observe protons of energy $E_n+0.78$ MeV produced by the (n, p) reaction with fast neutrons. The chief difficulty was to avoid masking by the high thermal neutron cross-section.[33] The (n, α) reaction in Li^6 has also been used in this way both in a LiI phosphor[34] and by distributing specks of Li^6 glass in a photographic emulsion.[35]

Neutrons of energy above a specific value may be observed if a reactive element with a suitable threshold is available. Fission detectors containing Np^{237} (E_T=0.1 MeV), Th^{232} (E_T=1.1 MeV)[36] and Bi^{209} (E_T=20 MeV)[37] have been widely used, while activation of C^{12} by the n, 2n reaction with a threshold of 20.4 MeV has also been employed. The most efficient way of observing the latter reaction is to expose an organic phosphor to the neutrons and then count the scintillations from C^{11} positron decay with a photomultiplier.[38]

Conclusion

It will be seen from the above discussion that measurements of thermal neutrons present no real problems, while recent developments suggest that much of the difficulty associated with fast neutron measurements is being removed. On the other hand, the low efficiency of organic phosphors for protons of energy below 100 keV, and the pile-up in gas counters of gamma-ray events to give spurious pulses of this order of energy, coupled with the absence of convenient thresholds or resonances in the keV region, all combine to make intractable the problem of specific detection of neutrons of intermediate energy, in the presence of thermal neutrons and gamma rays. This is the outstanding problem in the field of nuclear radiation detectors and, so far as published information goes, there seems to be no solution yet in sight.

REFERENCES

1. Sharpe. *Nuclear Engineering*, **2**, May, 1957, 191.
2. Bistline. *Rev. Sci. Inst.*, **19**, 842, 1948.
   Tunnicliffe and Fowler. *Ibid.*, **21**, 734, 1950.
   Sharpe and Salmon, A.E.R.E. Reports EL/R 1073 and 1239.
   Abson *et al.* *Proc. I.E.E.*, **105B**, paper M2542, Jan., 1958.
3. Abson and Wade. *Proc. I.E.E.*, **103B**, 590, 1956.
4. Jaques *et al.* *Ibid.*, **100B**, 110, 1953.
5. Gray *et al.* *Electrical Engineering*, **76**, 678, 1957.
6. Weaver *et al.* *Ibid.*, p. 665.
7. Abson *et al.* *Proc. I.E.E.*, **105B**, paper M2546, Jan., 1958.
8. Rae and Bowey. *Proc. Phys. Soc.*, **A66**, 1073, 1953.
9. Albert and Gaerfner. *Rev. Sci. Inst.*, **26**, 572, 1955.
10. Hanson and McKibben. *Phys. Rev.*, **72**, 673, 1947.
    Kushnerink. *Can. J. Phys.*, **30**, 402, 1952.
    Nobles *et al.* *Rev. Sci. Inst.*, **25**, 334, 1954.
11. Brugger *et al.* *Phys. Rev.*, **100**, 84, 1955.
12. Littler. *Proc. Phys. Soc.*, **A64**, 638, 1951.
13. Anderson *et al.* *Phys. Rev.*, **56**, 284, 1939.
14. Cleland. *Phys. Rev.*, **89**, 896, 1953.
15. Muelhause and Thomas. *Nucleonics*, **11**, No. 1, 44, 1953.
    Bollinger and Thomas. *Rev. Sci. Inst.*, **28**, 489, 1957.
16. Harrison *et al.* *Nucleonics*, **12**, No. 3, 44, 1954.
17. Wright. *Proc. Phys. Soc.*, **B69**, 358, 1956.
18. Brooks (Reference by Owen, in ref. 19).
19. Owen. *Nuclear Power*, **3**, April, 1958, 166.
20. Harding. *Nature*, **167**, 437, 1951.
21. Hornyak. *Rev. Sci. Inst.*, **23**, 264, 1952.
    Koontz *et al.* *Ibid.*, **26**, 352, 1955.
22. Taylor *et al.* *Phys. Rev.*, **100**, 174, 1955.
23. Sharpe. "Nuclear Radiation Detectors," p. 81, Methuen 1955.
24. Thomson. *Nucleonics*, **12**, No. 5, 43, 1954.
25. Rossi and Staub. "Ion Chambers and Counters," p. 184, McGraw-Hill, 1949.
    Holt and Litherland. *Rev. Sci. Inst.*, **25**, 298, 1954.
26. Rossi and Staub. *Ibid.*, p. 180.
27. Rossi and Staub. *Ibid.*, p. 176.
    Ward and Tunnicliffe. *Proc. Phys. Soc.*, **A65**, 233, 1952.
    Stafford. *Nature*, **162**, 771, 1948.
    Beghian. *Proc. Phys. Soc.*, **A62**, 395, 1949.
    Beghian *et al.* *Rev. Sci. Inst.*, **21**, 699, 1950.
28. Taylor and Sharpe. *Proc. I.E.E.*, **98B**, 181, 1951.
29. Bretscher and French. British Atomic Energy Report Br. 517. (See also Ref. 25, p. 182.)
30. Berlman. *Nucleonics*, **12**, 56, 1954.
31. Failla and Rossi. *Am. J. Roentgenology*, **64**, 489, 1950.
32. Hurst *et al.* *Rev. Sci. Inst.*, **22**, 981, 1951.
    Bracken *et al.* *Nucleonics*, **13**, No. 10, 70, 1955.
    Dennis and Loosemore, A.E.R.E. report, EL/R 2149, 1957.
33. Batchelor *et al.* *Rev. Sci. Inst.*, **26**, 1037, 1955.
34. Schenck. *Nature*, **171**, 518, 1953.
35. Roberts and Kinney. *Rev. Sci. Inst.*, **28**, 610, 1957.
36. Richards. A.E.C. Report LADC 908.
37. Wiegand. *Rev. Sci. Inst.*, **19**, 790, 1948.
38. Sharpe and Stafford. *Proc. Phys. Soc.*, **A64**, 211, 1951

Les Détecteurs de Neutrons—Une Etude

La mesure du flux neutronique thermique ne présente que peu de problèmes. Le détecteur le plus sensible employé généralement est un compteur proportionnel rempli de BF_3. Une chambre de ionization remplie de BF_3 possède une sensibilité moindre, mais peut pourvoir à flux plus elevés; le discernement des gamma n'est pas bon. Des chambres douclées de bore augmentent la gamme des flux neutroniques sans porter atteinte à la sensibilité des gamma. Pour des flux encore plus elevés, un nombre de piles thermoélectriques enduites de bore ont été developpées. Des compteurs de fission donnent de grandes pulsations de sortie et peuvent opérer dans des flux de gamma jusqu'à 10^5 r/h. Finalement, des feuilles activées sont communément employées pour des groupes infracritiques.

Les détecteurs neutroniques rapides se basent soit sur la thermalisation initiale des neutrons ou sur la mesure d'un flux de reculs de protons induits. On peut aborder la mesure de l'énergie de plusieurs manières et les mérites et les inconvénients de divers systèmes sont discutés dans cet article.

Neutron Detektoren—Eine Uebersicht

Die Messung des thermischen Neutronen-Flusses bringt nur wenige Probleme mit sich. Der empfindlichste Detektor, der in allgemeinem Gebrauch ist, ist ein mit BF_3 gefüllter Verhältnis-Anzeiger. Eine Ionisierungs-Kammer, die mit BF_3 gefüllt ist, weist eine geringere Empfindlichkeit auf, kann aber für grösseren Fluss gebraucht werden, wenn auch die Gamma Unterscheidung nicht gut ist. Mit Borfutter versehene Kammern erweitern die Reichweite des Neutronen-Flusses ohne die Gamma Empfindlichkeit zu ändern. Für noch grösseren Fluss sind eine Anzahl mit einer Bor-Schicht versehene Thermo-Meiler entwickelt worden. Spaltungs-Anzeiger geben starke ausgehende Pulse und können in Gamma-Flüssen bis zu 10^5 r/h arbeiten. Und schliesslich werden auch aktivierte Folien allgemein für Montagen unter der kritischen Grösse benutzt.

Detektoren für schnelle Neutronen beruhen entweder auf vorhergehender Thermalisierung der Neutronen oder auf der Messung des Flusses eines eingeleiteten Protonen-Rückpralls. Energie-Messungen können auf einer Anzahl von Wegen angefangen werden und das Für und Wider der verschiedenen Systeme wird besprochen.

Detectores de Neutrones—Un Estudio

La medición de flujo neutrónico térmico presenta pocos problemas. El detector más sensible en uso general es un contador proporcional llenado de BF_3. Una cámara de ionización llenada de BF_3 tiene menos sensibilidad pero puede proveer para flujos más elevados; el discernimiento de gammas no es bueno. Las cámaras revestidas de boro extienden el alcance de los flujos neutrónicos sin alterar la sensibilidad de gammas. Para flujos aun más elevados se han ideado diversas pilas termo-eléctricas revestidas de boro. Los contadores de fisión dan grandes pulsaciones de salida y pueden operar en flujos de gammas hasta de 10^5 h/r. Finalmente, se emplean generalmente hojas activadas para conjuntos infracríticos.

Los detectores de flujo neutrónico rápidos se valen de la termalización de los neutrones o en la medición de un flujo de reculadas de protón inducidas. La medición de energía puede hacerse de diversas maneras y en este artículo se discuten los méritos y las desventajas de los varios sistemas.

Hanover Trade Fair, 1958

Britain launches a world-wide sales campaign for power and research reactors with a complete nuclear fuel service. Nuclear engineering gathers momentum in Germany.

THE German Industries Fair at Hanover is a first-class display ground for any company alive enough to appreciate the challenge and the possibilities of the European common market. The Fair is typical of the post-war resurgence of German industry: each year it has expanded and new buildings have been erected.

The great strength of Hanover fair is in its international basis. Of the 4,320 exhibitors this year, more than 600 came from 20 foreign countries. Of these the U.K. had the third largest representation, with 73 companies. The organizers also made a special promotional effort in South America and a large contingent of buyers spent several days at the exhibition.

In 1957, on behalf of the A.E.A., the Board of Trade took space to show something of nuclear developments in the U.K. This year they were back in force with a two-part sales campaign—to sell fuel for power and research reactors and, in association with N.E.T.A.C., to sell British reactors and associated equipment.

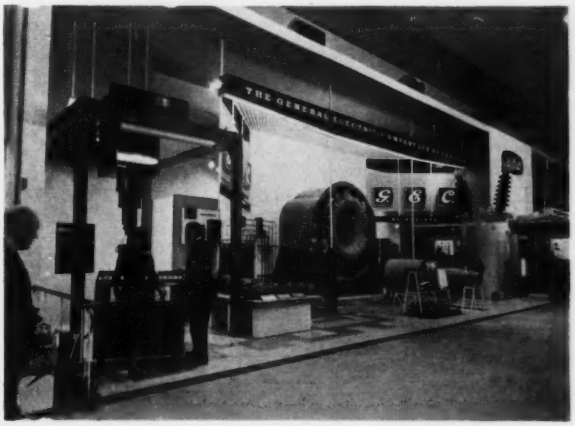
In principle the campaign at Hanover was excellent. The stand was large; it contained plenty of information and exhibits of interest. Visitors were able to operate a reactor simulator and a cinema attracted large crowds. On opening day a member of the Authority, Sir William Cook, spoke to a representative gathering of European journalists.

In spite of the obviously careful preparation of the stand, however, the display lacked coherency — probably because there was too much information. On the Authority's side the main story was of the work involved in producing and re-processing nuclear fuel. The medium chosen—photographs, colour transparencies, artist's impression, and diagrams with descriptive captions—often seemed to saturate rather than educate.

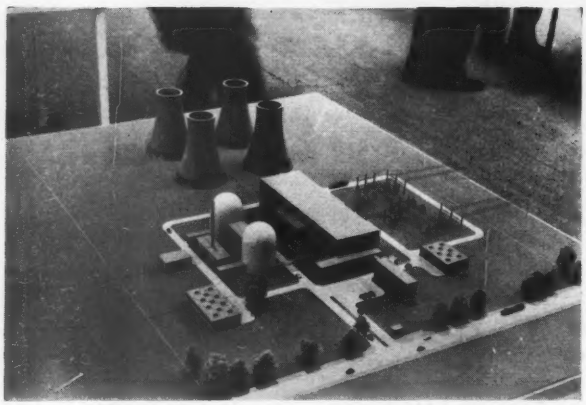
On the reactor side there were some excellent panels showing progress at Bradwell, Berkeley, Hunterston and Hinkley Point. A visitor might easily have gained the impression that Britain was building four completely different types of nuclear power station, rather than ingenious variations on the natural uranium, graphite moderated, gas-cooled theme. There was, too, an unfortunate phrasing of some captions. Understatements like "British industry is prepared to supply overseas countries with nuclear power plant to a value of £500 million by 1966," and "British manufacturing capacity is sufficient to meet demands from overseas for nuclear power" probably made many German industrialists smile.

Criticism in this respect should not be

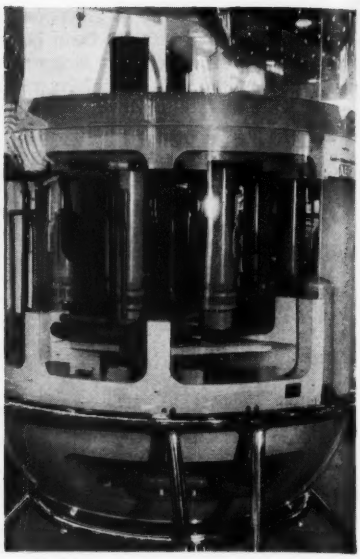
The principal nuclear exhibit at Hanover was the Board of Trade stand staffed by A.E.A. and N.E.T.A.C. personnel.



G.E.C. were the only large British company in the heavy electrical equipment hall. The powered manipulator is on the left.



(Left) The 200 MW reactor model on the stand of A.E.G. (Allgemeine Electricitätz-Gesellschaft).



A.E.G. also exhibited a sectional model of the BWR they propose to supply to a German electricity company. The pressure vessel has a diameter of 25 metres and is 51 metres high. Operating temperature is about 275° C.

allowed to overshadow recognition of the effort various people had put into the exhibit. There were plenty of A.E.A. and N.E.T.A.C. personnel available to answer questions and a supply of technical literature in various languages.

On the commercial side of nuclear energy British representation at the fair —apart from the display panels shown by the Board of Trade and N.E.T.A.C.—was almost non-existent.

Indeed, G.E.C. was the only major British electrical company in the heavy electrical equipment section. The G.E.C. has boldly decided to book a stand at Hanover for the next 12 years. The only exhibit of direct nuclear interest was the new powered manipulator. But it was undoubtedly the most spectacular piece of equipment on the stand and it attracted large crowds whenever it was in operation.

Principal German exhibit of nuclear interest was a model of a 200 MW boiling-water reactor station featured by A.E.G. The company hopes to conclude a contract for this type of station with a German electricity supply company in the near future.

On Demag's stand there was a model of Atomics International's proposal for an organic cooled and moderated marine reactor. Demag and A.I. recently formed a joint company, Interatom, which will, presumably, tender for any German power reactor required and, in view of Demag's extensive sales organization, also export reactors from Germany.

Other German companies with an interest in nuclear engineering included: Degussa (metallurgical research into uranium, thorium, zirconium, etc.), Marnesmann (thick steel plate for reactor pressure vessels), Oberhausen (steel with a cobalt content as low as 0.004%), Krupp (boron - aluminium alloys), Phoenix - Rheinrohr (clad metal of up to 224 mm thick), Industriewerke Karlsruhe (large-diameter bellows formed hot by a special spinning process), Heraeus Hanau and Leybold's Nachfolger (vacuum furnaces and vacuum pumps), Jenaer Glaswerk (remote viewing windows), and Boll and Kirch (radioactive water filters).

Instruments for nuclear application were exhibited by: Frieseke and Hopfner, Hartmann and Braun, Paul Firchow, K. G. Schomandl, Herfurth, and Rohde and Schwarz.

REACTOR G1 AT MARCOULE

THE natural-uranium air-cooled reactor G1, at Marcoule, came into operation on January 7, 1956, and was described in the first issue of *Nuclear Engineering* (April, 1956), so that it is by no means a new reactor—rather can it be counted amongst the pioneers and, as such, the record of "The World's Reactors" would be incomplete without its inclusion. G1 is air cooled and, in the original scheme, was intended as a plutonium-producing pile only, but was modified in the design stage to recover something over 5MW of electricity by means of an air-water heat exchanger, flash boilers, and a vertical turbine.

The method of cooling G1 is of particular interest in that the core takes the form of a horizontal prism, approximately cylindrical, with a narrow gap at the centre, through which the primary cooling air is supplied by means of a toroidal duct, being exhausted at the two ends of the core. Another point of interest is that criticality was achieved with some 20 tons of uranium.

As the drawing opposite shows, G1 is of imposing dimensions, although it was built in some 18 months of intensive effort. There are some 2,000 tons of steel in the bed-plate and 50,000 tons of concrete, mostly in the biological shield.

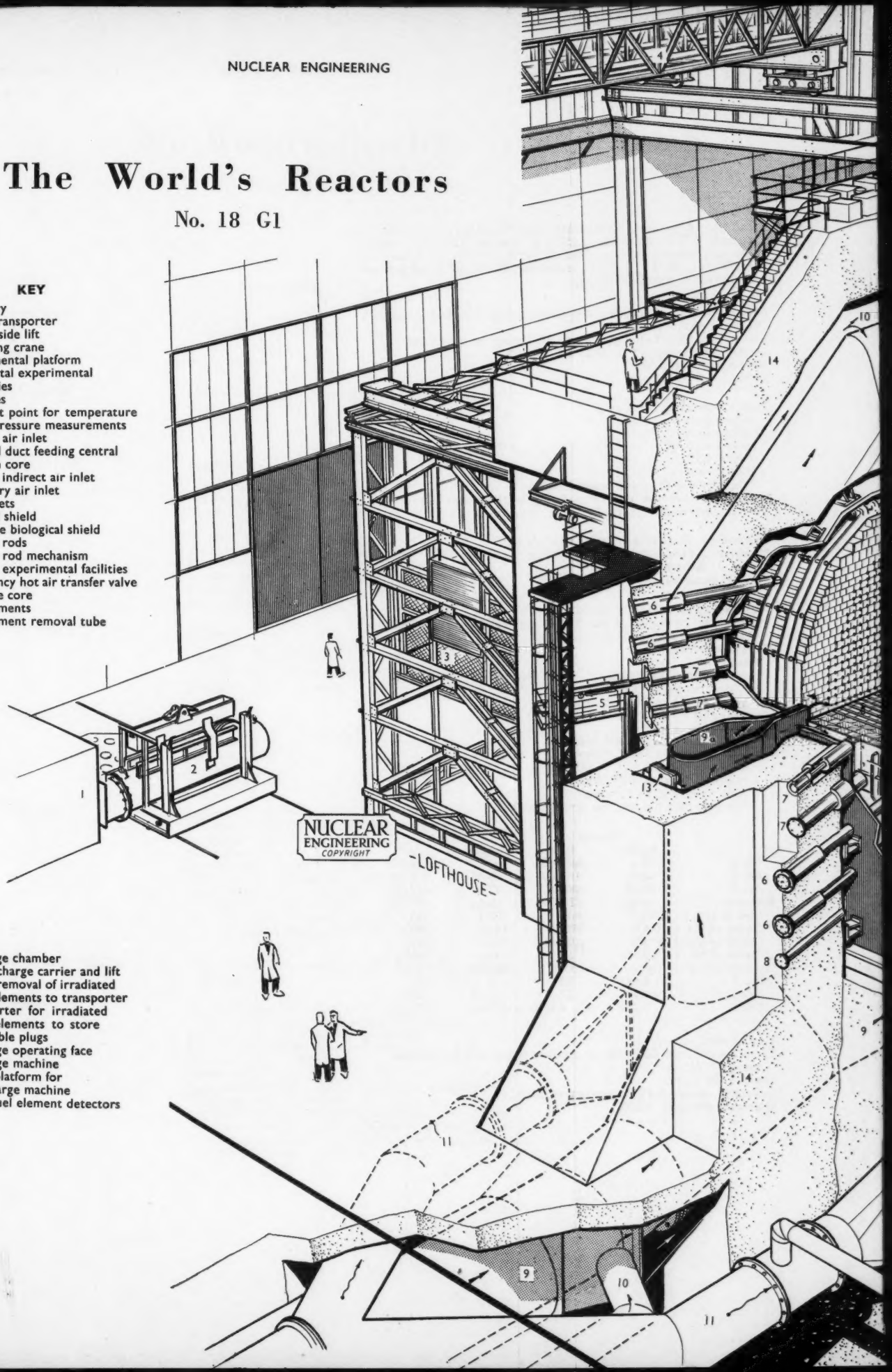
Marcoule, where G1 is located, is in the Gard department of Southern France, some 15 miles from Avignon, and is the headquarters of the Industrial Group of the Commissariat a l'Energie Atomique. Main contractor for the design and construction of G1 including graphite machining was the Société des Forges et Ateliers du Creusot (Usines Schneider) familiarly known as S.F.A.C. Working in close co-operation with them was the Compagnie Industrielle du Travaux (Enterprises Schneider) who were responsible for the concrete work. The heat exchanger was manufactured by the Société des Condenseurs Delas and the turbine by La Société Rateau. The alternator was built by the Société Generale de Constructions Electriques et Mecanique Alsthom. The Société Alsacienne des Constructions Mecaniques, who are manufacturers of instrumentation and burst slug detection equipment, provided the monitoring and instrumentation.

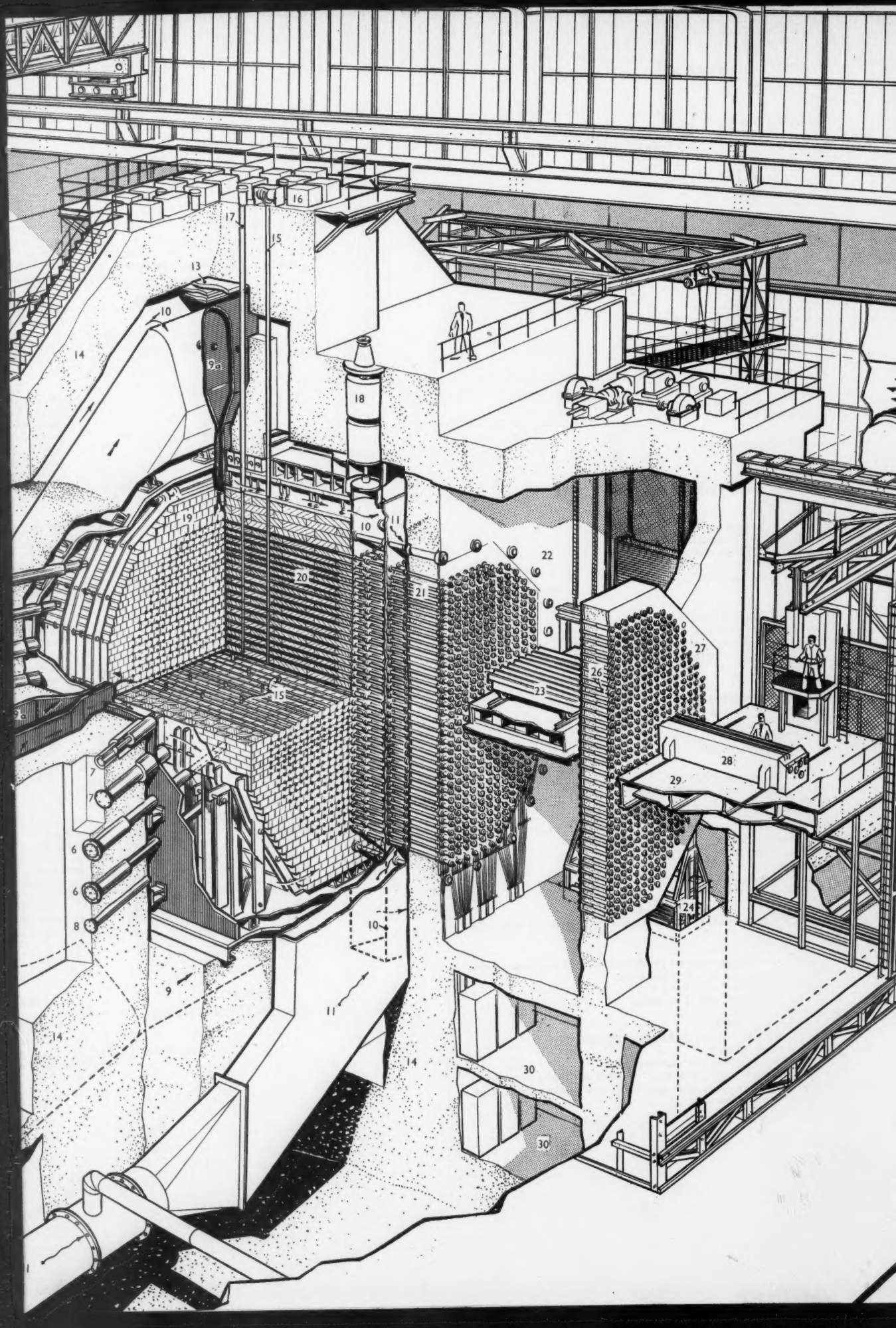
The World's Reactors

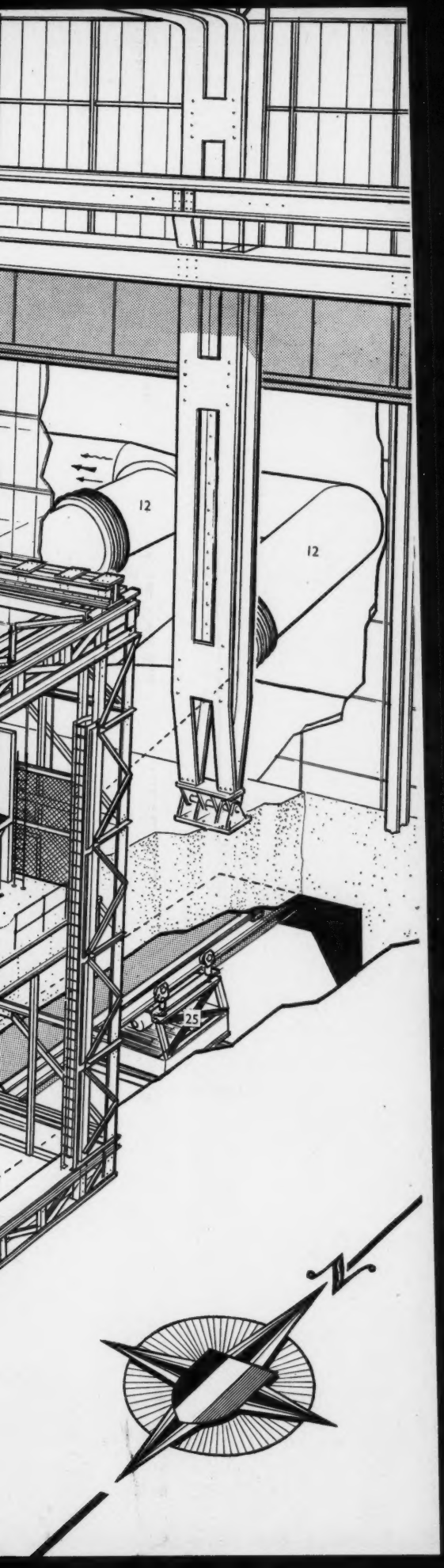
No. 18 G1

KEY

1. Mortuary
2. Coffin transporter
3. Charge side lift
4. Travelling crane
5. Experimental platform
6. Horizontal experimental facilities
7. Ion tubes
8. Lead-out point for temperature and pressure measurements
9. Primary air inlet
9a. Toroidal duct feeding central gap in core
10. Primary indirect air inlet
11. Secondary air inlet
12. Air outlets
13. Thermal shield
14. Concrete biological shield
15. Control rods
16. Control rod mechanism
17. Vertical experimental facilities
18. Emergency hot air transfer valve
19. Graphite core
20. Fuel elements
21. Fuel element removal tube
22. Discharge chamber
23. Fuel discharge carrier and lift
24. Lift for removal of irradiated fuel elements to transporter
25. Transporter for irradiated fuel elements to store
26. Removable plugs
27. Discharge operating face
28. Discharge machine
29. Lifting platform for discharge machine
30. Faulty fuel element detectors




16
17
15
13
10
14
9a
18
19
10
11
22
20
21
27
26
23
15
28
29
7
7
6
6
8
24
10
9
11
14
14
30
30
1


12
12
25

The World's Reactors

No. 18 G1

TYPE: Thermal heterogeneous.

PURPOSE: Plutonium production.
Prototype for central power stations.

LOCATION: Marcoule.

CAPACITY: Electrical rating: 5.75 MW normal 8 MW maximum.
Distribution: 5.5 kV.
Internal distribution: 380, 220, 127 and 48 V.
Heat rating: 40 MW.

OPERATION: Diverged 7th January, 1956.

FUEL: Natural uranium.
U as cast bars 26 mm (1.0236 in.) dia., 100 mm (3.937 in.) long, 37 bars in same sheath.
Density 18.9 g/cm³.
Elements in horizontal channels: two per channel.
Total weight of fissile material: 100 tonnes.
Number of fuel-element channels: 1,337.
Diameter of channels: 70 mm (2.7559 in.).
Maximum temperature: 400°C.

CANNING: Magnesium.
Wall thickness: 1.6 mm (0.0629 in.).
Diameter: 62 mm (2.441 in.).
Extended surface: 8 longitudinal fins 16.3 mm (0.648 in.) high.
Design maximum can surface temperature: 300°C.

MODERATOR: Graphite.
Core size: 8.225 m (26 ft 11½ in.) dia., 8.4 m (27 ft 6½ in.) long.
Thickness of reflector: 0.8 m (2 ft 7½ in.).
Total weight: 1,200 tons.
Blocks 200 mm (7.874 in.) square.
Average temperature: 125°C.

LATTICE: Regular square 200 mm (7.874 in.).
Thermal utilization factor, f : 0.895 ± 0.005.
Resonance escape factor, p : 0.912 ± 0.006.
Fast fission factor, ε: 1.029.
Thermal fission factor, η: 1.283.
Multiplication constant, k_∞ : 1.077.
Radial diffusion area, cm²: 376.
Axial diffusion area, cm²: 395.
Radial slowing-down area, cm²: 444.
Axial slowing-down area, cm²: 465.

PRESSURE VESSEL: There is no pressure vessel as such, the working pressure is practically atmospheric.

COOLANT: Air, distributed through a vertical gap 80 mm (3.1496 in.) wide in the centre of the core, fed by a toroidal duct.
Working pressure: 2 mm (78.74 in.) w.g.
Flow: 222 kg (488 lb)/sec with 3 blowers.
Inlet temperature: 20°C.
Outlet temperature: 200°C.
Mean coolant velocity: 37.5 m (123 ft)/sec in central duct.
There are three air circuits:
Primary direct, cooling fuel elements.
Primary indirect, cooling thermal shield and periphery of cylinder.
Secondary, cooling front and rear faces, and minimizing leakage from the primary channels.

BLOWERS:

Axial type, 4 primary, 4 secondary, coupled in pairs (1 primary, 1 secondary) each driven by 2,650 kW (approx. 3,500 h.p.) motor. Blower ratings. Primary: 240,000 m^3/h (141,000 cu. ft/min) at 2,200 mm (78.74 in.) w.g. Secondary: 80,000 m^3/h (47,000 cu. ft/min) at 650 mm (25.59 in.) w.g.

CONTROL:

Number of rods: 36 (32 safety and compensating, 4 automatic control).
Diameter: 43 mm (1.6929 in.).
Rod construction: boron carbide in two concentric steel tubes.
Length: 5 elements of 1 m (39.37 in.) per rod.
Suspension: steel cable.
Drive: $\frac{1}{4}$ h.p. motor.

REACTIVITY:

Total excess 5.7%, made up of:
- Neutron capture: 3.5%.
- Temperature: 0.7%.
- Samarium: 0.7%.
- Xenon: 0.7%.
- Miscellaneous: 0.1%.
- Reactivity due to central channel: 0.01%.

Control rod increment varies from 0.25% for the central rod to 0.04% for the outermost. Total 4%.

SHIELDING:

Thermal: 80 mm (3.1496 in.) thick steel plates.
Biological: concrete, 2 m (6 ft $6\frac{3}{4}$ in.) thick.
density, 2.5.
Cooling: blown air.

HEAT EXCHANGER:

Total heating surface: 5,800 m^2 (62,428 sq. ft).
Water tubes: Mild steel 21 mm (0.8268 in.) I.D., 26 mm (1.0236 in.) O.D., with 65 mm (2.559 in.) square fins.
Characteristics:
- Gas side:
  - Inlet temperature 180°C.
  - Outlet temperature 80°C.
  - Gas flow 257 kg (566.6 lb)/sec.
  - Inlet duct diameter 4.5 m (14 ft $9\frac{1}{2}$ in.).
- Water side:
  - Flow 61.2 kg/sec (486,000 lb/h).
  - Inlet temperature 60°C (140°F).
  - Outlet temperature 170°C (338°F).
  - Pressure 35 kg/cm^2 (497.82 p.s.i.).
  - Heat transfer 31.5×10^6 cal/h.
  - Efficiency 99% (i.e. 1% loss through walls).

BOILERS:

	Normal		Maximum	
Flow:	kg/sec	lb/h	kg/sec	lb/h
No. 1	61.2	486,000	92	730,000
No. 2	55.67	441,000	85.13	676,000
No. 3	50.69	400,000	77.06	612,000
Enthalpy	cal/kg	BTU/lb	cal/kg	BTU/lb
Inlet to No. 1	203.2	365.7	203.2	365.7
Outlet of No. 1	156.8	271.24	165.6	298.1
Outlet of No. 2	112.5	202.5	122.05	219.7
Outlet of No. 3	69.94	125.89	78.14	140.65
Steam pressure	kg/cm^2	p.s.i.	kg/cm^2	p.s.i.
No. 1	5.64	80	7	100
No. 2	1.57	22.4	2.14	30.4
No. 3	0.318	4.5	0.45	6.3

TURBO-ALTERNATOR:

Vertical shaft.
Continuous rating: 5.75 MW at a power factor of 0.8. Maximum rating 8 MW.
Speed: 3,000 r.p.m.
Generator voltage: 5.5 kV, three-phase, 50 c/s.
Alternator efficiency: 96.7%.

The Luce Ignition Scheme: Steady-State Injection in Thermonuclear Devices

By ALBERT SIMON

THE immediate goal of various thermonuclear programmes is to create a hot, fully-ionized gas (or plasma) whose temperature is sufficiently high so that appreciable thermonuclear reactions will occur.

A basic requirement in creating thermonuclear energy is that the temperature of the plasma must be greater than 100 million degrees, or an average particle energy greater than 10,000 electron volts. In addition, the plasma must be isolated from the walls of its container for tenths of seconds, or longer, if appreciable thermonuclear reactions are to occur.

One approach to this problem is illustrated by the Pinch effect and the Stellarator. In these, a cold gas is heated by an electrical discharge through the gas, and by various forms of magnetic squeezing.

Another method provides for individually-charged particles, already energized by a high voltage source or cascade accelerator, to be injected into a magnetic container (bottle) for trapping. This method is being pursued at Oak Ridge National Laboratory, which is operated by Union Carbide Corporation for the U.S. Atomic Energy Commission.

The Oak Ridge approach, advanced by John S. Luce, is to accomplish this energetic injection and trapping through molecular breakup. This procedure calls for a high energy (600 keV) molecular deuterium ion to be injected across the magnetic field which serves to confine the ions.

The molecular ion is a charged system of two deuterium nuclei (ions) and an electron. Ordinarily, the molecule moves in a large circle within the magnetic field and returns to strike the source from which it is injected. However, the molecule can be dissociated into two particles: a singly-charged deuterium ion, and a neutral deuterium atom composed of the remaining deuterium nucleus and the electron.

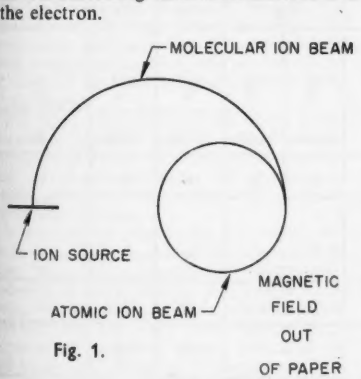


Fig. 1.

After dissociation, the neutral atom flies out of the system because it no longer is contained by the magnetic field. The remaining ion, however, now circles in a new orbit half the radius of the original circle. Thus, if the dissociation is accomplished at the other edge of the molecular orbit, then the resultant ion is trapped since it does not return to strike the source (Fig. 1). This is called the Luce Ignition Scheme.

The method means little unless one actually has a means of dissociating these molecular ions with high efficiency and in the right regions. John Luce in his research on various forms of gaseous discharges has discovered an unusual type of arc discharge which has just this property. The combination of an arc discharge of this type, together with a confining d.c. magnetic field and high energy molecular injection, constitutes a class of thermonuclear experiments which has been designated as DCX (for d.c. experiments).

The detailed structure of the arc discharge and the reason for its high dissociation efficiency are as yet imperfectly understood, and it is suggested that the existence of this arc and its ability to dissociate a large fraction of the molecular beam be accepted as empirical facts, and consideration be given to the conditions which must be met in order to obtain a thermonuclear plasma.

For illustration, injection and trapping in a mirror geometry will be considered.

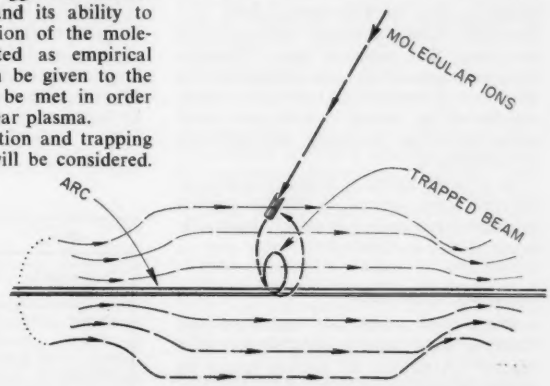


Fig. 2.

This is the easiest way to use the Luce Ignition Scheme, although it is possible to envisage its use in a Stellarator geometry, or even in the Pinch. A simple system is shown in Fig 2, the arc being run through the mirrors. The energetic deuterium molecular ions are injected across the field and are partially dissociated and trapped as shown.

This illustration has been greatly simplified, since it shows trapped particles moving in a single organized ring current. Actually, these orbits will spread out because of energy loss and the non-uniform nature of the confining magnetic field. Trapped particle paths will cross each other, and the desired nuclear reactions can then occur.

There are several competing actions undesirable to this scheme, one of which is charge exchange. If neutral gas atoms are in the plasma, an energetic ion can steal an electron from this atom and itself become electrically neutral. Because this energetic neutral atom is no longer confined by the field, it escapes. As a result, the inner system must initially be pumped down to very low gas pressures to prevent such an energy drain on the system. In addition, it may be necessary to utilize the trapped beam itself for additional clean-up of residual gas in the container.

An important advantage of this scheme for producing thermonuclear plasma is the fact that there should be no ambiguity about the arrival at a thermonuclear state. For example, in a typical case one would obtain a total neutron yield from the volume of about 10^{12} to 10^{13} per second with a 1 milliampere input of ions. This same number of ions fired into a solid deuterium target would yield only about 10^{8} per second. An increase of the yield from 10^{8} to 10^{13} could only be accounted for by the heating of the electrons and the formation of a plasma.

Of course many possible difficulties may arise. The arc itself, for example, may have unfavourable as well as favourable features. Fortunately, one of the most serious of these is known to be absent. Measurements by Barnett have established that less than one in 10^{5} fast protons (300 keV) suffer a charge exchange in passing through the arc. The presence of the arc may contribute impurities as well as moderately cold electrons which tend to hold down the energy of the plasma. It should be kept in mind that the arc should be thought of as a plasma "igniter" rather than as a permanent feature of a thermonuclear device. Once a partial plasma has formed, one would hope to shut off the arc and continue feeding the gas by using the molecular breakup occurring in the residual plasma. If, indeed, the plasma is

(*Continued on page* 263)

ZIRCONIUM v. STAINLESS STEEL

Comparative Economics in the U.S.

RESULTS of an extensive scientific study on the economics of zirconium v. stainless steel as a cladding and structural material in nuclear power reactors have been released by Columbia-National Corporation. The study, which was more than a year in preparation, was made by Dr. Manson Benedict, head of the Nuclear Engineering Department of Massachusetts Institute of Technology.

Symposia sponsored by Columbia-National in New York and Pittsburgh were attended by more than 150 representatives of leading reactor designers and builders, electric power companies and the A.E.C. as well as other zirconium sponge producers, melters, converters and mill products manufacturers, and provided additional information, supplementing the basic study, to assist industry in determining where it is economically feasible to take advantage of the superior nuclear properties and corrosion resistance of zirconium.

The use of zirconium instead of stainless steel makes possible savings through the use of uranium of lower enrichment, reduction in the critical mass of uranium, or a combination of both. On the other hand, zirconium and its alloys cost more than stainless steel. The economic incentive to use zirconium is, therefore, dependent on the relative magnitudes of the saving in fuel costs compared with the additional material cost of zirconium.

Five power reactors with fuel materials varying from natural to highly-enriched uranium were studied in detail; the results being shown in Table 1.

Summary of Results

Break-even prices of zirconium and stainless steel were computed for each reactor. Assuming an annual return on capital investment of 15%, the break-even price is defined as the price at which the lower cost of uranium inventory obtained through use of zirconium is just balanced by the difference in cost between zirconium and stainless steel.

Important conclusions brought out by the Benedict report are:

1. Zircaloy should be used for permanent parts of commercial power-producing reactors fuelled with uranium enriched up to at least 4% U^{235}.

2. Zircaloy should be used to clad fuel elements of natural uranium.

3. At prices of from $40 to $60 per pound for mill products, Zircaloy appears to be competitive with stainless steel at $5 per pound for fuel cladding in slightly enriched reactors in which zirconium can be substituted for stainless steel on approximately a volume-for-volume basis.

4. The break-even price is roughly inversely proportional to the volume of Zircaloy substituted for one volume of stainless steel.

5. The break-even price of Zircaloy decreases as the U^{235} enrichment of the fuel increases, because neutron economy is less important with more highly enriched fuels. Should the A.E.C.'s rental charge against the value of the entire inventory of uranium (now only 4%/y) be raised to a level more representative of commercial interest rates prevailing both here and abroad, the break-even price of zirconium would be increased significantly. This will also be the result if the price of enriched uranium is raised.

6. A study of the effect of power factor indicates that Zircaloy should be seriously considered for cladding fuel elements, as well as permanent parts, in reactors which are likely to be operated at load factors below 80%.

7. For a reactor operating at a given power level, the break-even price of Zircaloy increases as it becomes possible to increase the lifetime of the fuel in the reactor, i.e., as the fraction of fuel which is burned is increased, a higher price can be justified for the Zircaloy. The break-even price of Zircaloy also is higher with longer fuel lifetime for a given burn-up fraction, since the Zircaloy need not then be replaced so frequently.

8. A significant measure of the economic incentive to use Zircaloy in preference to stainless steel is the annual return on the incremental investment made when substituting Zircaloy for stainless steel. At the break-even price, the return is 15%. As the prices of Zircaloy mill products are reduced below the break-even price, the return on the incremental investment rises sharply.

General agreement with the results of the Columbia-National study was shown by industry representatives attending the two symposia.

Dr. W. K. Lewis of Canada has expressed the view that for a small, 20-MW (E), heavy water demonstration reactor, allowing a tolerance of 10% in the pressure tube wall thickness jeopardizes a capital expenditure of $300,000. He is, therefore, more ready to pay a good price for Zircaloy if it meets a high metallurgical and corrosion-resistance specification and tight dimensional tolerance.

By polling the leading mill products manufacturers, Columbia-National determined that the price range of zirconium tubing today is $40 to $60/lb. Analysis of the costs on which these prices are based indicates that further price reductions can be expected. One major producer stated that an ultimate price of not more than $30/lb for tubing can be expected.

Tubing prices were of importance to the Benedict study because most of the

TABLE 1. REACTORS STUDIED

Name	NPD	S.G.R.	Yankee		Merchant Ship		Vallecitos B.W.R.
Developed by ..	A.E.C. of Canada Canadian G.E.	Atomics Internat.	Westinghouse		Babcock and Wilcox		General Electric
Owner	Hydroelectric Power Comm. of Ontario	Consumers Public Power of Nebraska	Yankee Atomic Electric Co.		Maritime Comm. and A.E.C.		G.E. and Pacific Gas and Electric
MW (E)	20	75	134		—		5
MW (H)	80	250	480		85		20
% U^{235} in fuel ..	0.71	1.8	2.6		3.64		93
Load factor ..	0.8	0.8	0.8		0.8	0.4	0.6
Fuel cladding thickness, 0.001 in.							
S.S.	30	10	15	15	26.5	26.5	5
Zr	30	10	15	30	38	38	5
Pounds Zr per charge.. ..	3,045	1,920	10,940	22,400	7,700	7,700	584
Break-even price, $/lb ..	104	57	51	25	44	57	10
Permanent parts thickness, 0.001 in.							
S.S.	40	35	—		Equal	Equal	—
Zr	40	35	—				—
Pounds Zr per reactor ..	2,970	15,060	—		3,270	3,270	—
Break-even price, $/lb ..	842	592	—		141	109	—

reactors examined will use tubular fuel elements filled with uranium oxide pellets. It was assumed that the tubes to be used were for the second core of a given reactor; lower yields and high fabrication costs are usually incurred with first core production.

Expectation of lower cost zirconium mill products was substantiated by manufacturers of such items attending the second symposium in Pittsburgh, March 11. Greater volume of production will be an important factor in cost reduction. Additional savings are expected to result from higher yields, better re-use of scrap and improved processing techniques already in the planning stages.

Dr. Daniel Gans, Stone and Webster Engineering Corporation, emphasized the problem of radiation hazard associated with cobalt-containing alloys of stainless steel when used in reactor cores. Studies over the past five years indicate that substantial amounts of radioactive cobalt may be deposited in the outer portions of the primary coolant loops of power reactors, and that a significant part of this comes from stainless steels containing only small amounts of cobalt. Such radiation problems, resulting over an extended period of operation, might preclude the use of less expensive grades of stainless steel in reactor cores. An increase in cost of stainless steel increases the break-even price of zirconium by approximately the same amount.

Correspondence

Consulting Engineers

In response to an editorial "The Role of Consulting Engineers," in our August 1957 issue, the following communication has been received from the Association of Consulting Engineers Inc.

LIKE their colleagues in other established professions such as law and medicine, professional Consulting Engineers are not permitted by the ethical rules of their Association to advertise. That is to say, they cannot directly inform the public of their personal achievements or abilities, or those of their respective firms.

Such restriction is recognized by all qualified consulting engineers as necessary to maintain the high ethical standards and the integrity of the profession but, of course, it has its disadvantages. There is much lack of knowledge outside the profession itself of the functions of consulting engineers and the circumstances in which they can be most advantageously employed.

The main function of consulting engineers is to give the client strictly impartial and disinterested expert advice and, where required, to undertake design, placing of contracts, inspection and the supervision of construction on site.

Where major works are involved, such as a power station, the consulting engineer would be called in to deal with, or advise on, the very considerable amount of preliminary work (including choice of site) necessary before detailed designs can be commenced. Thereafter, following design studies, specifications have to be prepared, and normally there will be many specifications corresponding to the various parts of the work for which separate competitive tenders can with advantage be obtained. Then there is the work of comparing and reporting on the tenders received, followed by the placing of orders. Subsequent functions include the checking of all contractors' drawings, the progressing and inspection of materials and plant during manufacture, the supervision of all work on site, and the final commissioning of the works.

The most obvious circumstance in which consulting engineers can be advantageously employed is where the client—due either to lack of expert knowledge or shortage of staff—cannot himself satisfactorily perform the above functions.

In the case of large works, with which this letter is mainly concerned, the client will in most cases be a public, or semi-public, authority of some sort, or else a large company. Such clients must consider first whether or not they have within their organization sufficient expert personnel to undertake the functions in question. This consideration has become especially important in view of the extreme and growing shortage of qualified technologists. To perform adequately the work which is normally undertaken by consulting engineers, the client must carry a staff not only capable of dealing with the average yearly level of his new construction work, but also with the peak requirements. This may be both difficult and costly.

Assuming, however, that staffing requirements can be met, the client must then ask himself whether his staff can bring to bear an equal, or greater, degree of expert knowledge, and at least as unbiased an approach, as that of a leading firm of consulting engineers. This question may be quite difficult to answer, especially bearing in mind the very rapid advance in techniques.

The large firms of consulting engineers may, very rightly, claim a particularly wide and varied experience obtained both at home and abroad. They may also have specially studied and equipped themselves for the type of work in question.

In regard to the avoidance of bias, this is an even more difficult consideration, though very important. In most large, long-established public organizations there is a certain tendency towards "inbreeding" of technical thought, and it is very important to try and avoid this. Consulting engineers are less affected by this tendency because of the variety of their work and their contact with all sorts of clients, both at home and abroad. Some leading authorities in this country may take the very sensible view that the best results will be obtained by contact between their own staff and that of leading consulting engineers, with some degree of friendly competition in the carrying out of new works, some engineered by the authority's own staff and some by consulting engineers.

It may be thought that considerable differences exist between civil consulting engineers, on the one hand, and mechanical and electrical consulting engineers on the other. The most apparent difference is that the civil consulting engineers seem to do more design work than their mechanical or electrical colleagues. The latter can indirectly influence the manufacturers' design of electrical and mechanical apparatus, but in general their function is to discriminate between alternative designs of plant rather than themselves to design. Nevertheless, this difference is more apparent than real because, in the construction of major projects such as power stations, a tremendous amount of design is called for in laying out and fitting together the component parts of the station, and in the initial selection of the most appropriate temperatures, pressures and other vital parameters.

Furthermore, the leading firms of mechanical and electrical consulting engineers who handle complete projects are accustomed to take overall responsibility for the design and construction of all associated civil engineering works, often associating with themselves appropriate firms of civil consulting engineers.

It is significant that the importance of competition in the obtaining of tenders is constantly being emphasized in reports of Royal Commissions and other impartial bodies. At the same time, due to the formation of ever-larger contracting or manufacturing units or groups of such units, the difficulty of getting adequate competition is increasing. Experience indicates that where full competition is not obtained, e.g., because of purchasers accepting "all-in" bids, the costs of major works are liable to be very substantially increased above those of truly competitive bidding. If competitive "all-in" bids are requested on the basis of only a general specification (leaving detailed design to the contractor), there is great difficulty, when the bids are received, in comparing one offer with another. Moreover, manufacturers and contractors, quite rightly, point to the very heavy and unproductive costs in which they are involved in preparing large numbers of designs and detailed tenders of which only one in a considerable number is acccepted. In the long run the contractors' costs will be reflected in tender prices and will, therefore, be paid by the purchaser.

The only reasonable solution of this dilemma is for designs and detailed specifications to be prepared by the purchaser, or his consulting engineers, thus greatly reducing the costs incurred by the manufacturer or contractor in tendering, and also making tenders truly comparable.

In the field of nuclear power the position is particularly complicated by the extreme novelty of the work in question, the existence of the nuclear manufacturing "groups" and the very important part played by the Atomic Energy Authority. It does, however, seem probable that as the design of nuclear power stations becomes somewhat more established and backed by actual operating experience, the purchaser will wish to exercise more

discrimination than he can at present. He will no doubt wish, as soon as conditions permit, to break down the nuclear power station into a series of component contracts and to place each contract as a result of competitive tenders, just as he does for conventional power plants today. Long years of experience have demonstrated that only by adopting this procedure can the purchaser get what he really wants throughout the job at the lowest overall cost. The purchaser's engineers, or the consulting engineers where they are employed, can accurately forecast the overall performance of the plant by means of guarantees obtained for each of the component parts.

Even if an "all-in" offer is still desired, clients may well find the services of consulting engineers, to assist in the comparing of offers and in actual design, of special value.

The foregoing does not by any means cover all the considerations which the client must take into account, and in regard to the principal nationalized industries it is proper that some consideration should be paid to the importance of consulting engineers' work abroad. This work can be regarded as a spearhead of the country's export drive and, therefore, of very great importance. Obviously, consulting engineers cannot easily operate abroad unless they have a background of up-to-date work and experience at home.

In the light of all these, and other, considerations, consulting engineers are, in fact, being employed widely by the principal authorities in this country, including the Central Electricity Generating Board, the Atomic Energy Authority, the South of Scotland Electricity Board, the North of Scotland Hydro-Electric Board, and the Electricity Board for Northern Ireland. The national shortage of technological staff has been a particularly important consideration, and for this and other reasons the future employment of large firms of consulting engineers, especially those who have equipped themselves for work in new fields, such as nuclear energy, would seem to be reasonably assured. A statement issued by the (then) British Electricity Authority in August, 1951, is of considerable interest in this connection:—

> "While the staff of the British Electricity Authority is carrying out the design work for the majority of new power stations, a proportion of these projects is being entrusted to consulting engineers as a matter of policy. In coming to the decision to supplement the work of its own staff in this way, the Authority says that it has had in mind the widening of experience resulting from the utilization of the existing organizations of consulting engineers and the national importance of the work which consulting engineers do abroad."

There are, however, a number of important organizations in this country who, for the reasons mentioned earlier are not sufficiently informed either as to the functions of modern highly organized firms of consulting engineers or as to the best way of using them. It is hoped that this may help to give such information and to dispel misconception.

B. Donkin, M.Inst.C.E., M.I.E.E.,
Chairman, 1957/58,
The Association of Consulting Engineers (Inc.)

(Since the above was written we have learned from the Chairman of the Central Electricity Generating Board that in future the design and supervision of construction of the Board's Generating Stations will be done by their own staff with the exception that Consultants will be retained, when required, to give specialist advice on certain aspects of design, mainly of a civil engineering nature.)

Technical Papers and Publications

THE INSTITUTION OF ELECTRICAL ENGINEERS

Supply Section, in conjunction with B.N.E.C.

Operational Experience at Calder Hall.

By K. L. Stretch, M.A., A.M.I.E.E. (N.C.B., formerly U.K.A.E.A. I.G.)

The commissioning routine at Calder after reactor No. 1 was taken over by the operations branch in May, 1956 had a four-fold object: First, it was necessary to confirm that a reactor of this type really did operate efficiently; that it would operate economically, and, although optimized for plutonium and not as a power producer, it would at least yield an indication of future possibilities. It was also desired to confirm the safety characteristics and to establish problems and limitations of this type of reactor; its stability, flexibility, and life of fuel elements.

The station was commissioned to a very tight time schedule, and a high degree of preparation and co-ordination was necessary. The commissioning team was built up during the 18 months before take-over. Working parties were formed, representing the research establishments and design office, as well as the operations branch, to work out a programme in detail, and as soon as the method was established, the operations branch carried out the detailed planning necessary to ensure speedy accomplishment.

Fuel Charging

The fuelling of No. 1 reactor commenced on May 19 as soon as final acceptance tests had been completed. Loading was carried out mostly by hand, and it was desired to obtain a cylindrical shape for the critical mass. By the evening of May 22, the doubling time indicated that criticality had been obtained with a smaller fuel load than expected, and a series of foil irradiations and doubling times were taken. It had originally been planned to test the effect of channels with steel absorbers and

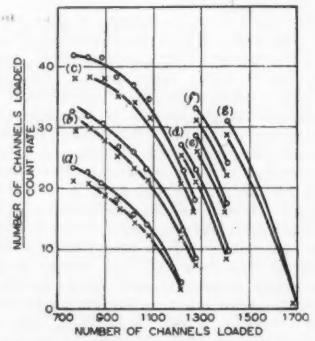


Fig. 1.—Loading to full size: approach-to-criticality curves.

o Counter No. 2.
x Counter No. 3.
Number of control rods inserted:
(a) 20. (d) 26. (f) 30.
(b) 22. (e) 28. (g) 32.
(c) 24.

enriched uranium, but it was decided that with the small critical size, enrichment would be unnecessary, and only the effect of steel absorbers was measured.

During the charging to critical size fast withdrawal of the control rods had been used to speed up measurements, but this was not considered admissible during the second stage. To speed up matters, a number of control rods were detached from their mechanisms and left fully inserted, the number being calculated so as to be short of the amount required to keep the reactor sub critical when fully charged. The remaining rods were held in the fully withdrawn position so that they could be dropped immediately for counteracting any unexpected approach to critical. Charging then proceeded in a number of controlled approaches to critical, extra rods being inserted as the build-up in reactivity balanced those already in place (Fig. 1). The loading in this case was by the charge machines working in groups of 16 channels (or 8 channels) where a complete group caused too much distortion from the cylindrical shape.

It was clear that the 70 control rods of the original design were not necessary, and a revised pattern of 52 was selected for calibration, which was carried out by exhausting the vessel to the highest possible vacuum and then gradually pressurizing it in steps, balancing each

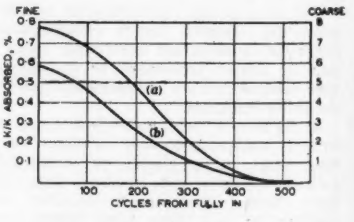


Fig. 2.—Control-rod calibration.

(a) 4 fine rods.
(b) 40 rods.

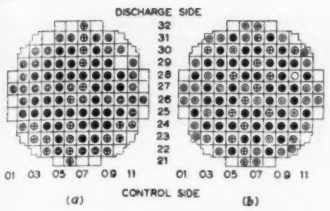


Fig. 3.—Pattern on reactor top.

(a) Reactor No. 1.
(b) Reactor No. 2.
Equipment in charge tube.
● Control rod.
⊙ Thermocouple.
⊕ Flux scanner.

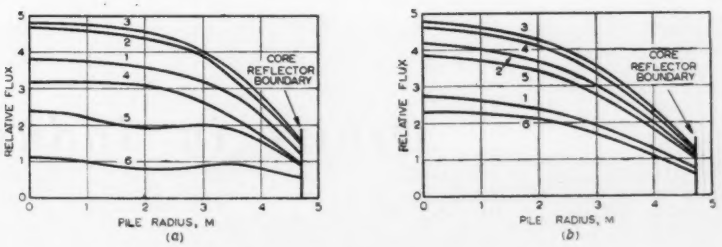


Fig. 5.—Radial flux distribution (through centre of cartridges).

(a) 136 MW: control rods at 306 cycles; initial pattern.
(b) 180 MW: control rods at 500 cycles; revised pattern.

increase in air pressure (and, therefore, of neutron-absorbing nitrogen) by a rod withdrawal. Calibration curves are shown in Fig. 2. By now results of calculations made during charging were available and the excess reactivity established as 5.6% instead of the 4.2% originally expected, and it was decided to trim down to 4.5% with steel rods. This enabled the control rods to be reduced to 40, which would provide 6% reactivity control, thus allowing a number of additional experimental facilities, such as flux scanners and thermocouples to be inserted.

Mechanical Testing

Air flow measurements at atmospheric pressure were carried out to check the flow pattern after charging, and to ensure that no obstructions existed. The reactor was then pressurized with carbon dioxide and a programme of leak tracing and tightening was carried out, followed by a four-day run at full blower power during which the four gas circuits were checked for balanced flow. It was then blown down, during which surrounding regions were checked for CO_2 concentration. The charge and discharge machines were tested with the full purging routine. The entire reactor was then purged, filled with air, and inspected internally.

The burst cartridge detection gear was then tested and modifications carried out to prevent the high background signal built up due to argon activity. At the same time, defects were discovered in the fuel element spiders (see paper by H. G. Davey before the Institution of Chemical Engineers *Nuclear Engineering*, February, 1958, page 79). During this time, a clean-up was made of a quantity of oil which had found its way into the reactor through mal-operation of a valve on one of the blower seal oil-detraining systems.

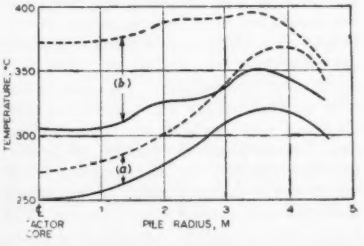


Fig. 4.—Radial temperature distribution.

- - - - - Temperature of top cartridge.
——— Gas outlet temperature.
(a) 136 MW: control rods at 306 cycles; initial pattern.
(b) 180 MW: control rods at 500 cycles; revised pattern.

Power Operation

The system was first heated by injecting steam into the heat exchangers from an auxiliary boiler, and circulating gas. After checking the temperature coefficient and control-rod calibration, the reactor was worked up to about 130 MW, safety valves being floated and automatic trips tested, as well as complete radiation surveys all over the plant. All the steam was passed to the dump condenser until the third week in August, when the turbines were commissioned.

After the official opening by H.M. the Queen, the reactor was taken up to full power, when it was found that only 170 MW of heat could be extracted owing to the "cold centre" effect, caused by a bad flux distribution pattern due to the mass of absorber concentrated around the centre. Retrimming of the reactor during a shut-down in early November, resulted in the ability to withdraw the rods further and improve the temperature distribution.

No. 2 Reactor

The second reactor was handed over and, during December, an intense experimental programme was carried out to fill some of the gaps in information, this being concentrated on measurements on different sizes and shapes of core, and No. 2 reactor was trimmed more closely to the correct excess reactivity with 48 control rods. Figs. 3a and 3b show the patterns of the two reactors. It was still found that the outlet temperature was low (about 320°C) and modifications to the gagging pattern were necessary.

The next operation was the complete recharging of Reactor 1, to replace bowed fuel cartridges with braced units and to modify the gagging and control-rod patterns. Reactor No. 1 finally gave an outlet temperature of 330°C with improved flux and temperature distribution (Figs. 4 and 5).

(*Continued from page* 259)

well above the ignition point the high energy injection could be shut off entirely and cold feed used to sustain and even increase the plasma. The ideal operating energy of an actual operating reactor is well below the 300 kV injection energy used in the previous illustrations and is more like 60 kV.

Other possible difficulties are things like partially ionized impurities, heat conduction to the walls, and instabilities. In the case of partially stripped impurities there again seem to be advantages to working down in energy.

Heat conduction to the walls may be serious. It is in the very nature of the Luce Ignition Scheme that the particles are deposited only 1 Larmor diameter of the atomic ion from the injection snout. The resultant heat transfer rate, if calculated assuming a linear temperature variation to the surface, could be appreciably larger than the bremsstrahlung loss. However, simple calculations are possible to show that heating from above still forces the final temperature to be of the order of 75 kV or more. From a long-range view one will want to compress the plasma once after its formation in order that it then be capable of retaining its own reaction products and be self-sustaining. This step would also take care of the heat transfer problem.

Finally, there is the question of instabilities. This is still very much an open question, particularly since the theoretical assumptions to date make use of hydrodynamic models which are far from valid at these larger Larmor radii and since they omit the effect of electric fields. In any event, it would seem that a steady state device is an excellent one for studying the possible onset and control of these instabilities if they exist.

At Oak Ridge, research using the above-mentioned concepts has been under way for some time. Although the experimental and theoretical problems are difficult and involved, considerable progress has been made. Detailed reports of these results will be presented in the future.

Orbits in Industry

THAT often misquoted proverb, "A prophet is not without honour, save in his own country," does not always hold good, as most of us know. Many a man who draws a lot of water (or cuts a lot of ice, as summer's coming along) in his own organization gets a rude shock when he goes out into the cold hard world, and nowhere does this happen more frequently than when a technical type goes "on the road." He may be a citizen, as it were, of no mean city, a senior executive of a reasonably sized manufacturing company, and his mission may be totally unconnected with direct selling. Nevertheless, unless he has a cast-iron contact already, he is apt to have his attention drawn, kindly, resignedly or rudely (depending on the reception arrangement), to a little notice that impresses one with the fact that Travellers can be Seen on Tuesdays and Thursdays Only.

Obviously, no organization of any size can stay in business without centralized purchasing. One could imagine the chaos existing in a large engineering works if everybody was buying stuff for their own particular jobs and, taking it to extremes, one could imagine inch-by-eighth black mild steel being purchased in 6-foot lots. Nevertheless, centralized purchasing, however economical it may be for dealing with stuff that is used by the ton, has its own disadvantages when it comes to the specialized odds and ends, particularly if the buying department has old-fashioned ideas. By "old-fashioned" is meant the pre-war outlook that was summed up so neatly—and so venomously, if it comes to that—more than twenty years ago by Mr. C. E. Smith, then vice-president of the New York, New Haven and Hartford railway.

. . ." *The typical buyer is a man past middle life, spare, wrinkled, intelligent, cold, passive, non-committal; with eyes like a codfish, polite in contact, but at the same time unresponsive, cool, calm and as damnably composed as a concrete post or a plaster of paris cast; a human petrification with a heart of felspar and without charm or friendly germ, minus bowels, passions, or a sense of humour. Happily, they never reproduce, and all of them finally go to hell.*" . . .

While it is a trifle harsh to use the term "typical," it must be admitted that buyers like that did exist. The war thinned out their ranks, during the topsy-turveydom of the sellers' market, when the limited supplies of many things were disposed of under the Old Pals Act, and many a buyer was left wishing that he had realized that even the so-called "commercial traveller," the subject of so many ribald stories, was a human being, and that he had gone a little easier on the dust-beneath-my-chariot-wheels routine. Some of them even took it to heart.

Watertight Compartments

The chief trouble nowadays is usually an inability on the part of the buying department to realize not only that times have changed but so also have the callers. Frequently they are not even trying to make a sale. But, unless the buyer is a technical man, "service" or good-will calls are wasted. If the caller's company makes retractable gnurgling-sprockets, he wants to see the technical man who is toying with a new idea that needs a retractable gnurgling-sprocket to make it workable, and who will welcome sound advice on some point that is worrying him. What he does not want, however, is to cool his heels in a waiting-room for an hour and then be told that there's nothing today but he can leave a price list and discount schedule.

It is not easy, in a company of any size, to ensure that every caller sees the man who really needs him, and the bigger the organization the more difficult it becomes. Those who do not at least try to ensure that there is efficient liaison between the technical staff and the purchasing department will be the poorer in the long run.

Down Memory Lane

All through the film "Measure of Maxam" (briefly noted elsewhere in this issue) Tangent was wondering why the name "Holman Group," with which he is reasonably familiar, suddenly seemed to take on a new significance. The long-buried memory finally struggled to the surface. . . . Of course! The Holman Projector!

Way back in 1940 when small ships were going to sea with armament that was, to say the least of it, inadequate, a benefactor (presumably Mr. Holman himself, since it bears his name) produced this remarkable piece of ordnance (almost falling into our select classification of an Ingenious Device) for use against low-flying planes. Operated by compressed air or steam, as available, it projected a Mills bomb high into the air. (Unless, of course, someone had turned the steam off, when it gave what Kipling used to call "a 'appy little belch" and dribbled the bomb out on the deck, thus giving the bystanders the opportunity of earning a medal or being distributed over the surrounding seascape). Since, however, a lot of people would have been grateful in those days for a reasonably powerful cross-bow, arquebus, or culverin, the name of Mr. Holman became as blessed as the saintly Abbot of Aberbrothok.

A vivid mental picture still lives on of the first one delivered to Lowestoft, undergoing tests at the hands of two elderly gunnery officers. One, acting as loader, was busy with a clasp knife, trimming large potatoes, and dropping them down the spout. The other, combining the functions of gunlayer, control officer, rangefinder and fall-of-shot spotter, was solemnly discharging them—at low-flying seagulls.

Random Reflections

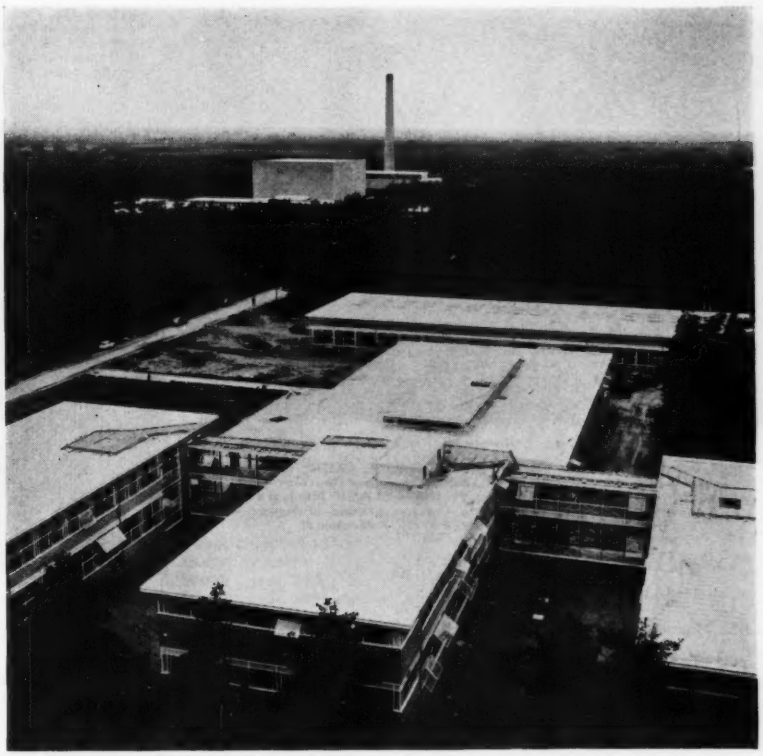
(With apologies to Ogden Nash).

Whether the neutrons so far obtained from ZETA
were—or were not—thermo-nuclear
Even the boys who worked on it don't seem
any tuclear;
And whether they come from deuterium collision
or other internal commotion
They haven't a notion.
Perhaps the steady-state injection (page 259) pro-
posed by Luce
Might be some uce;
(Although the thought of an imaginary magnetic
mirror
Seems quirror and quirror).
But lots of people (of which I myself am one)
Think ZETA publicity a bit overdone;
And, frankly, get a little bit weary
Of the song and dance about the temperature
of the sun's inteary;
All that it conveys to most of us is that it gets
very hot
So what?
Maybe, a studious avoidance of any further
ballyhoo on ZETA
Might be discreta.

Kremlin-Expresso

After (but not, of course, because of) the peevish note in April regarding the inaccessibility of A.E.A. personnel in the House of a Thousand Windows (and 999 catches) their new home in Charles II Street, the photographic department has now moved outside the security barrier. One can now walk in on them without any formality at all—except, of course, the genuflection in the entrance hall which every decently bred person would automatically accord the Authority. The Press boys, of course, are still in solitary, presumably in the dungeons below the moat. Here, sitting haggard and unshaven on their straw mattresses, they listen, wincing, to the whistle of the lash and the screams of an unfortunate colleague, who has inadvertently sent a hand-out to a journal the day *before* it goes to press. By contrast, the Photographic's new premises are so contemporary that it was recently mistaken for a new coffee bar, with the Perspex model of Dounreay in the window as the Expresso machine. . . . The sad part of this bit is that it's true. How much more satisfactory imagination could have made it!

Tangent



Many foreign scientists visiting the Universal Exhibition in Brussels are also taking the opportunity to see something of Belgium's nuclear research centre at Mol. Camouflaged in a beautifully wooded area, the centre now contains a large number of research laboratories with various reactor projects in course of development.

World News

International

Over 200 fellowships are now available to the International Atomic Energy Agency (I.A.E.A.) the director-general, Mr. Sterling Cole, told a Geneva press conference on May 7. The initial programme of the Agency has been focused on the training and exchange of scientists and experts. The large number of fellowships obtainable (total value more than $1 million) will enable the Agency to place many technicians and scientists during the next academic year beginning this autumn.

Board of Governors of the I.A.E.A. met from April 24 to May 6 in Vienna. As a result of the Board's decisions a first draft of the 1959 programme and budget is being prepared for approval at the next meetings, which begin on June 16. The second session of the general conference opens in Vienna on September 22.

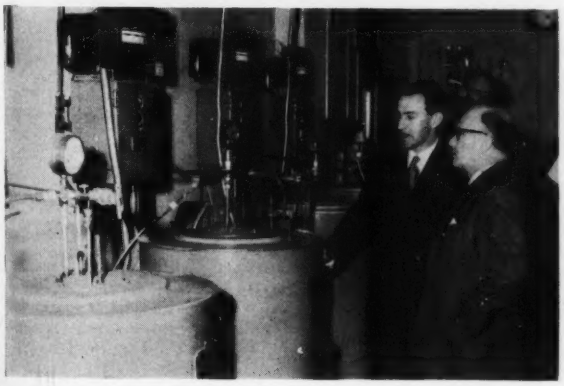
Two mobile radioisotope laboratories are being presented to the I.A.E.A. by the U.S., Mr. Robert M. McKinney head of the U.S. delegation announced recently. The laboratories—designed by Oak Ridge Institute of Nuclear Studies for basic training in radioisotope handling techniques—will cost $85,000.

European Insurance Committee held a preliminary meeting of insurance company representatives from the six Euratom countries at the end of April. The committee proposes to hold a convention on civil responsibility arising from nuclear incidents in peacetime. The initial talks discussed general conditions affecting claims.

European Nuclear Energy Agency held a similar meeting ten days later with the object of inaugurating an insurance convention covering all the O.E.E.C. countries. Eventually both conventions may amalgamate.

United Kingdom

Thermonuclear reactions are not the source of the majority of neutrons produced by ZETA according to Dr. Thoneman, head of the Controlled Thermonuclear Research Division at Harwell. An elegant experiment using a diffusion cloud chamber to measure the energy spectrum of the neutrons emitted by the plasma in a collinated beam has shown that the predominant reaction is between deuterium ions of 20 keV energy and slow moving ions. It is believed that ions are accelerated by the surge in electric field imposed on the gas but the magnitude of the energy attained is surprising and no satisfactory theory has yet been evolved to explain completely the results. The experiment in no way invalidates the measurements previously made with ZETA as calculations from neutron intensity on the temperatures achieved agreed only approximately with those measured by spectrographic means. Neutron intensity was also at variance with the expected value derived from a theoretical estimate of energy exchange between the electrons and ions. Efforts being made to increase the plasma current from 200 kA to 1,000 kA if successful should assist by throwing further light on the acceleration process and should also show whether thermonuclear reactions are at the same time taking place. In addition other methods of initiating the nuclear flame are under investigation. Further work in the U.S.A. over that reported in the joint release at the end of January has markedly increased neutron production but equivalent spectrum measurements have, as in this country, indicated that this is not thermonuclear in origin.



During his visit to the G.E.C. research laboratories at Erith, Prof. Balke (right) was shown furnaces for studying the oxidation of metals at elevated temperatures and pressures in atmospheres of carbon dioxide or mixtures of carbon dioxide with carbon monoxide and water vapour. He is seen here with Dr. K. J. Wooton, manager of G.E.C.'s atomic energy division.

Prof. Dr. Ing. Siegfried Balke, West German Minister for Nuclear Energy, visited the U.K. from May 13 to 18 at the invitation of the Board of Trade. Prof. Balke had discussions with the four nuclear consortia and visited the Bradwell site, G.E.C.'s atomic energy research laboratories at Erith, and Industrial Group H.Q. at Risley.

Main cause of delay in choosing a site for a nuclear power station in N. Ireland is the public safety aspect, the Minister of Commerce, Lord Glentoran, told the House of Commons recently. The station is scheduled for operation in 1963.

(Above) Prior to the signing of the N.P.P.C.—AGIP Nucleare agreement, Sir Claude Gibb, K.B.E., F.R.S., chairman, Nuclear Power Plant Co., greeted Signor E. Mattei, President of AGIP Nucleare and of Ente Nazionale Idrocarburi. In the background is Signor G. Martinoli, managing director of AGIP Nucleare.

(Below) On May 12 Mr. Selwyn Lloyd (left), Britain's Foreign Secretary, and Signor Vittorio Zoppi, Italian Ambassador in London, exchanged instruments of ratification bringing into force the Anglo-Italian atomic energy agreement. The ten-year agreement provides for the supply of both research and power reactors together with the necessary nuclear fuel.

Mr. Macmillan rejected a request to establish a joint working party between the A.E.A. and Euratom during question time in the Commons recently. At present the U.K. has bilateral agreements with five of the six Euratom countries, he said. The Government is considering methods of co-operation.

First of the 12 Bradwell heat exchangers was landed at Bradwell Waterside on May 19. On the previous Friday it was launched by the manufacturers, Head Wrightson, at Thornaby-on-Tees. It was towed down to Bradwell over the week-end. The remaining boilers—each 92 ft long and weighing 200 tons—will be delivered in the same way at six-weekly intervals.

Australia

Technical mission from U.S.A.E.C. will visit the symposium on the peaceful uses of atomic energy in Sydney during the first week in June. The mission will also have talks with the Australian A.E.C. following the bilateral agreement between the two countries which came into force last year.

Brazil

Plans for the installation of 10 MW nuclear power stations in Brazil and Cuba have been suspended, the American and Foreign Power Co. announced on May 13. Conventional generating units will be now installed in both countries.

Hungary

Hungary and the U.S.S.R. signed an agreement for co-operation in the peaceful uses of atomic energy in Moscow on April 30. The agreement provides for Soviet scientific and technical assistance in return for uranium mined in Hungary. The Hungarian delegation was led by Arpad Kiss, chairman of the state planning committee.

Israel

United States will contribute $350,000 toward the cost of a nuclear research reactor project planned by Israel A.E.C. The project will be located at the Commission's nuclear centre near Rehovot. The reactor will be a 1-MW heterogeneous-pool type installed by AMF Atomics, of New York. The Israel Government estimated the cost of the nuclear and associated facilities to be $1,410,000. The United States will lease the necessary fuel to Israel under the terms of the research agreement for co-operation in the peaceful uses of atomic energy. Israel's, research reactor will be made available to research scientists and engineers through educational institutions, hospitals, industrial laboratories or by direct contact with Israel A.E.C. The primary purpose will be to train personnel in theory and operation. The staff will include scientists trained at the International School of Nuclear Science and Engineering at Argonne National Laboratory.

Italy

The anticipated agreement for long-term collaboration between Nuclear Power Plant Co. and AGIP Nucleare of Milan was signed recently, and it is expected that a contract will shortly be placed for a single-reactor 200-MW power station. The site chosen is near Latina, about 50 miles south of Rome. The operating company will be the Societa Italiana Meridionale per l'Energia Atomica (SIMEA), jointly owned by AGIP Nucleare and Institute per la Riconstruzione Industriale (IRI). N.P.P.C. will be responsible for the overall design of the station and the supply of major components including the heat-exchangers and turbines, the total value being some £20m. An exchange of personnel has already taken place between the two companies.

Nine companies have submitted tenders to SENN for the construction of a nuclear power station in Southern Italy. British concerns include A.E.I.-John Thompson, English Electric and G.E.C., Simon-Carves and Mitchell Engineering. The others are Atomics International, International General Electric, H. K. Ferguson, Kaiser Engineers and Société Générale de Constructions Electroniques et Mecaniques of Paris.

Japan

Negotiations between the U.K. and Japan leading to an agreement between the two countries are expected to be concluded before the end of May. A delay had been caused by Japan insisting that either the U.K. Government or the Authority should be liable for any risks in handling nuclear fuel. The Japanese Government has now agreed to accept ordinary insurance cover for any claims which might arise.

Spain

U.K.A.E.A. took 1,000 sq ft of space at Spain's first international atomic energy exhibition which opened in Madrid on May 10.

United States

EBWR — Experimental Boiling Water Reactor at Argonne National Laboratory—has been shut down temporarily for repair work on a defective turbine. Mr. Joseph M. Harrer, associate director of Argonne's Reactor Engineering Division and project manager of EBWR, said the turbine was damaged when a blade snapped at the root. Repairs are expected to take about one month; the reactor itself is undamaged. It is important to note that levels of radioactivity in the turbine are low enough to permit inspection and repair in a routine manner; typical values range from 0.05 to 0.2 mr/h.

Mrs. Richard M. Nixon, wife of the U.S. vice-president, was due to lay the keel of the first commercial nuclear-powered ship, the N.S. Savannah, in the yard of the New York Shipbuilding Corporation on May 22.

U.S.A.E.C. announced on May 8 that domestic producers of uranium ores and concentrates could now sell them privately at home and abroad. All sales will be subject to licensing by the Commission. Materials such as U^{233}, U^{235} and plutonium will remain under Government control. A similar decision has been taken by the Canadian Government.

Among recent visitors to Argonne National Laboratory were (left) Dr. John M. Poole, senior scientific officer, A.E.R.E., Harwell, (centre) Mr. E. N. Shaw, editor, *Nuclear Engineering*, and (right) Mr. Peter Scofield, senior scientific officer, A.E.R.E. They are seen here with (second from left) Dr. Norman Hilberry, laboratory director, and Mr. David Saxe, deputy director, Chicago operations office, U.S.A.E.C.

An organic moderated reactor is to supply power to the city of Piqua; agreement has finally been reached between the U.S.A.E.C., the city and Atomics International following proposals made in response to the second invitation under the Power Demonstration programme. The station of 12.5 MW(E) capacity is to be built on the Great Miami River and should be completed by July, 1961. The commission's contribution which includes research and development is estimated at $12.3M and the conventional facilities are costed at $4M.

A serious leak has developed in the core container of HRE2. Although the failure cannot be seen it is believed that a split 1½ to 2 in. long has occurred in the zirconium vessel at the junction of the 45° and 30° cone, immediately above the flow spreaders. Thermal stresses may have been increased at this point by the build-up of fuel, but another cause is probably the known anisotropy of the plate which was available at the time of construction. Repair is virtually impossible but Oak Ridge propose to proceed with experiments either as a single zone or two-zone system; operation as a single zone will require a concentration of effort on the chemical processing system. It is understood that although the leak is obviously undesirable the reactor will still remain a useful piece of research and experimental equipment.

ETR, the high power testing reactor at the N.R.T.S., Idaho Falls, has been run up to 175 MW. Although certain commissioning modifications are still going on, the process of pinning fuel plates into elements rather than brazing has eliminated the distortion at high coolant velocities. Problems still remain on the locating of the ion chambers and with the regulator rods, which controlled less reactivity than expected, but the first testing loops are being installed.

Reloading the Brookhaven pile with enriched fuel has reached the end of the first phase to give a power rating of 12 MW. This central-entry air-cooled pile was previously loaded with 60 tons of natural uranium and developed 28 MW (clean) and 20-24 MW at equilibrium with 48 tons; thermal flux was about 5.10^{12} n/cm², sec. The new elements use over 90% enriched U^{235}, are 2 ft long, star shaped in section with the vane tips turned over and the initial loading is over a diamond-shaped section approx. 25 channels high by 13 channels wide. Results indicate that 25% burn-up can be achieved and that the thermal neutron flux is 2.5. 10^{13} n/cm², sec. As burn-up proceeds fuel cycling will be introduced and the core made cylindrical. Flux will then increase to 3.10^{13} and a total burn-up of 40% is expected with a full loading of 40kg U^{235}. The reactor is shortly due for a Wigner release so the Windscale accident and the more recent BEPO release have been studied with considerable interest.

Reactors for process steam production are to be developed by Lockheed Aircraft Corporation. The company has recently set up a new branch at Marietta, Ga., called the Georgia Nuclear Laboratories to undertake design. Preliminary studies concentrate on the water-cooled and moderated type but smaller in size than those normally under investigation. No detailed report has been issued, but the company has stated that with particular reference to the pulp industry, process steam can be provided at a cost comparable with that from conventional fuels in the high cost areas in the U.S.A. The A.E.C. is to be asked to assist in financing initial projects.

A.E.C. Licences and Permits. To A.C.F. Industries for export of a 30 MW tank-type, light water-cooled and moderated research reactor to Aktiebolaget Atomenergi, Sweden. Value of the shipment is estimated at $1,850,000. To Curtiss-Wright for operation of a 1 MW pool-type research reactor at Quehanna, Pennsylvania.

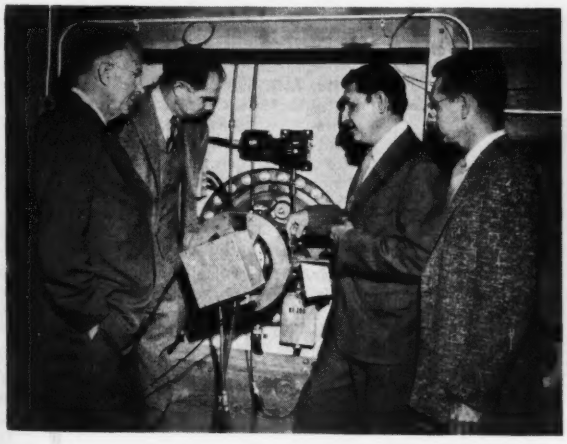
U.S.S.R.

Kazakhstan's first research reactor is to be installed at a new nuclear centre near Alma Ata, the Kazakh capital.

Yugoslavia

First research reactor, purchased from the U.S.S.R. and erected near Belgrade went critical recently.

(Below) Dr. Albert Ghiorso (third from left) on May 5 challenged the findings of the international group of scientists who claimed to have discovered nobelium at Stockholm last July. Dr. Ghiorso said that a research team from the University of California had produced nobelium on April 18 after they had unsuccessfully tried to duplicate the Stockholm experiment.



An international team of twenty-one scientific secretaries has been appointed for the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, to be held in Geneva, 1-13 September of this year. Seen here at U.N. headquarters are six members of this international group (from left to right): Mr. William Woollen (United Kingdom); Mr. Hiroshi Fukunaga (Japan); Mr. Pierre Y. Tanguy (France); Mr. Cesar Sastre (Argentina); Mr. Terence E. F. Carr (United Kingdom) and Dr. Claudio Garavaglia (Italy).

Personal

Appointments

Mr. H. H. Gott

Mr. G. Deane

Mr. R. H. Cooke

Mr. H. H. Gott, M.A., A.M.I.Mech.E., chief engineer, reactor design in the industrial power branch of the Atomic Energy Authority as nuclear plant design engineer of the Central Electricity Generating Board.

Mr. R. H. Cooke as director and general manager of Research and Control Instruments.

Mr. D. D. Morrell as managing director of Mitchell Construction Co. The company are the main civil engineering contractors at Chapelcross.

Mr. A. J. S. Ashton and **Mr. R. D. Young** as directors of Tube Investments.

Mr. A. D. Jenkins, M.Eng.(Liverpool), A.M.I.E.E., as divisional chief engineer, Smith's Industrial Instrument Division.

Sir Sam H. Brown as an additional director of Vickers. **Sir Thomas R. Merton,** K.B.E., F.R.S., retires from the Vickers board on June 2.

Mr. R. C. Hesketh-Jones, LL.B., formerly sales director (industrial division) British Oxygen Gases, as chief executive (overseas) at British Oxygen's head office. **Mr. R. J. Foster,** D.F.C., A.F.C., M.A., director and general manager of British Oxygen Aro Equipment, succeeds Mr. Hesketh-Jones.

Mr. H. W. Fender, M.Inst.B.E., A.C.I.S., vice-chairman and managing director of Prodorite, Ltd., as chairman of the British Chemical Plant Manufacturers' Association for 1958.

Mr. L. W. Anderson, until recently chief project engineer with Miles Structural Plastics, Ltd., as chief project engineer at Wemyss Woodhouse, Ltd.

Mr. H. S. Davidson, T.D., M.I.E.E., transmission engineer, Midlands Division, C.E.G.B., as divisional controller, South-Western Division.

Mr. J. L. Gray, M.Sc., vice-president, administration and operations, Atomic Energy of Canada, succeeds **Mr. W. J. Bennett,** O.B.E., B.A., LL.D., as president.

Dr. John H. Williams as director of the research division, U.S.A.E.C. He succeeds **Dr. Thomas H. Johnson,** who resigned last October to manage the research division of Raytheon Manufacturing Co.

Mr. R. J. Henry as president, Eldorado Mining and Refining.

Sir Douglas Veale, C.B.E., until recently registrar at Oxford University, has accepted the chairmanship of a committee set up by the A.E.A. to advise on training in radiological protection. The committee includes **Sir Ernest Rock Carling, Prof. W. V. Mayneord** and **Prof. B. W. Windeyer.**

Mr. J. R. Moore as a director of Fisher Governor Co. (a member of the Elliott-Automation group).

Mr. D. F. Craig as a director of Liquid Systems.

Mr. R. W. Addie as marketing director of E.M.I. Electronics.

Mr. Gilbert Deane, chief engineer, Chatwood-Milner, assumes responsibility for the company's new sound insulation and nuclear protection division.

Mr. Thomas Johnston, chairman, North of Scotland H.E. Board, succeeds Viscount Chandos as president, British Electrical Development Association. **Lt.-Col. E. H. E. Woodward** becomes vice-president.

Mr. Sebastian Z. de Ferranti as managing director, Ferranti. **Sir Vincent Ferranti** remains chairman.

Colonel B. H. Leeson, director, B.E.A.M.A., as the new chairman of the board of governors, Faraday House.

Following the death of **Mr. F. Briggs,** F.C.I.S., secretary of William Jessop and Sons and J. J. Saville and Co., **Mr. D. Milne,** C.A., has been appointed secretary with **Mr. J. V. Gregory** assistant secretary.

Mr. John T. Bailey as chief design engineer of Vitro Engineering Co.

Messrs. **Paul R. Fields, Lawrence E. Glendenin, Gerhart R. Hennig, John R. Huizenga, Bernard Smaller, Ellis P. Steinberg, Robert J. Thorn** and **Philip H. Yuster,** of the chemistry division, and **Martyn H. Foss,** of the particle accelerator division, Argonne National Laboratory, as senior scientists of the laboratory.

Mr. J. E. Jonsson as chairman, and **Mr. Patrick E. Haggerty** as president, of Texas Instruments Inc.

Mr. L. H. J. Phillips, B.Sc., A.M.I.E.E., sales manager, electronics dept., as assistant commercial manager, Metropolitan-Vickers Electrical Co., Ltd. **Mr. A. G. Barton,** Assoc.R.T.C. (Salford), A.M.I.E.E., succeeds Mr. Phillips as sales manager, electronics dept.

Mr. Lewis Hart as chairman, and **Mr. C. T. M. Bagnall** as vice-chairman, of B.E.A.M.A. publicity committee.

Mr. Baron, formerly director-general of the aluminium division of the Pechiney Co. of France, as director-general of the company's nuclear division.

Tours

Mr. D. W. Payn, general manager and secretary to the Lead Development Association, recently returned from a two-week visit to the United States and Canada.

Mr. Peter Wright, sales engineer, Short Bros. and Harland, has just undertaken a survey of the potential market in Canada for Short's general-purpose analogue computer.

Dr. J. C. Simmonds, M.Sc. (Eng.), Ph.D., M.I.E.E., M.I.Mech.E., managing director, Airmec, visited Switzerland early in May to explore the market for Airmec industrial electronic equipment.

Mr. H. S. Davidson

Mr. D. D. Morrell

Mr. A. D. Jenkins

Obituary

Nuclear Engineering records with regret the deaths of the following:—

Mr. W. McDonald, managing director of both the Hackbridge Cable Co. and Bryce Electric Construction Co., on May 6 at the age of 65.

Mr. P. H. Muirhead, C.B.E., who until January this year was managing director of Vickers-Armstrongs (Engineers), Ltd., on April 27 at the age of 53.

Industrial Notes

The English Electric, Babcock and Wilcox, and Taylor Woodrow Atomic Power Construction Co., Ltd., is the title of a new company formed to administer the 500 MW Hinkley Point contract. Directors are Mr. H. G. Nelson (English Electric), Mr. H. McNeil (Babcock and Wilcox) and Mr. F. Taylor (Taylor-Woodrow).

English Electric have been awarded a contract by the C.E.G.B. for the supply of a 15-circuit duplicate busbar switching station for Hinkley Point nuclear power station. The order, worth £980,000, covers generator, feeder, station transformer and bus coupler circuits as well as 14-7,500 MVA air-blast circuit breakers.

Automatic Telephone and Electric Co., English Electric and Ericcson Telephones have formed a company called **Associated Transistors** for the development and manufacture of transistors and other semiconductor devices. A 55,000-sq-ft factory is being erected at Ruislip, Middx.

Associated Electrical Industries has purchased the capital of Associated Insulation Products from Elliott-Automation.

Carl Wezel, of Mühlacker, West Germany, has now completed the rolling mill for the production of uranium rods which is to be installed at Trombay by the Indian A.E.C. Estimated cost of the mill is £12.5 million.

Central Electricity Authority's stand at the Production Exhibition (Olympia, London, May 12 to 21) featured the progress made in the generation of electricity by nuclear means.

Research and Control Instruments have been appointed sole distributors in the U.K. for Philips and Mullard electronic and scientific instruments and electro-chemical apparatus. The new company has offices at Instrument House, 207 Kings Cross Road, London, W.C.1. Phone, Terminus 8444.

European Free Trade occupied the thoughts of many of the speakers at the Scientific Instrument Manufacturers' Association annual luncheon at the Savoy, London, on May 15. Appropriately, the guest of honour was the Paymaster-General, Mr. Reginald Maudling, the Minister responsible for Free Trade discussions. He was told by the SIMA president, Mr. P. Goudime, that the great majority of SIMA members welcomed free trade. Already the 150 members of SIMA had begun to work together to streamline the instrument industries in the U.K. Through the Scientific Instrument Research Association a consultancy service was available to members. A technical inquiry service for customers was now linked with the Instrument Centre at 20 Queen Anne Street, London, W.1. (Telephone: IMP 6000.)

Electronic Associates of Long Branch, New Jersey, recently shipped the first electronic analogue computer to the Japanese A.E.C.

Gem Power Brushes is the new title of Gem Brushes (Luson).

The Serck Group have acquired new London offices at 60-61 Trafalgar Square, W.C.2. Telephone: Trafalgar 4401-3. The London technical staff of the following companies will be located there: Serck Radiators, Serck Tubes and Audley Engineering.

Pye have received an order for a television nuclear reactor camera for the C.E.G.B. station at Bradwell. The first Pye TV camera, of 3 in. diameter and 40 in. long, was used at Calder Hall. The camera had its own source of illumination and a special cooling system was provided. A second camera, supplied for examination of the Windscale pile, incorporated facilities for remote handling.

Atomics International, a division of North American Aviation, recently announced a $1¼ million building programme to expand nuclear field laboratory facilities near Los Angeles. The site is about one mile from the SRE reactor in the Santa Susana Mountains, about 10 miles N.W. of Canoga Park.

Bristol Aeroplane Group's annual report—commenting that the company is pursuing a small but growing research programme for the Authority—says that it is hoped to derive significant turnover from applying to nuclear energy the metallurgical knowledge gained in work on ramjets.

Chatwood-Milner have formed a sound insulation and nuclear protection division which will be responsible for the production of doors for atomic energy projects.

Swan, Hunter and Wigham Richardson announced on May 6 that the company is to collaborate with Nuclear Power Plant Co. in the development of nuclear-powered merchant ships.

Martin-Nuclear, a division of the Martin Co., has started production of flat plate fuel elements for the company's zero power reactor experiment under contract with the United States Army, Corps of Engineers. The experiments, which are scheduled to begin in the Martin zero power test facility, are intended to advance the technology of portable pressurized water reactors.

M. and C. Nuclear Inc., of Attleboro, Massachusetts, have recently opened an 11,200-sq-ft addition to their laboratories. The company, a subsidiary of Metals and Controls, Corp., manufactures nuclear fuel and complete reactor cores.

Brush Beryllium Co., of Cleveland, have been awarded a $1,200,000 contract for the fabrication of two beryllium-core matrices for the BR2 under construction at Mol, Belgium.

British Oxygen Gases are building a new factory near their existing premises at Polmadie, Glasgow.

N.G.N. Electrical, manufacturers of high-vacuum equipment, have moved to new premises at Avenue Parade, Accrington.

Kerry's (Ultrasonics), Ltd., of Tonbridge Road, Harold Hill, Romford, Essex, have taken over the distribution of the low-powered range of Mullard ultrasonic equipment in the U.K. and certain overseas markets.

Mullard have offered Oxford University £50,000, payable over a 10-year period, towards the cost of a new college.

Mullard have established a new product group, the semiconductor division, to co-ordinate the company's activities in this sphere. Mr. G. A. Gilbert, M.B.E., B.Sc., is in charge, with Mr. P. A. L. Harris, B.Sc. (Eng.), A.M.I.E.E., as commercial manager and Mr. G. D. Grimsdell as technical manager.

Ekco Electronics and **George Kent** are now offering their joint services for the contracting, engineering and manufacture of instrumentation schemes for both power and research reactors. Both companies have already collaborated in the instrumentation of four heavy-water research reactors—Kent producing the physical instruments and recorders and Ekco concentrating on nucleonic aspects.

American Nuclear Society moves on July 1 to the John Crerar Library, 86 E. Randolph Street, Chicago.

Deionization (Elgar), Ltd., has been formed by Elga Products to cover home sales and service of industrial deionization equipment.

Associated Electrical Industries have organized a training scheme for officers leaving the services as a result of recent defence cuts. Prepared in conjunction with the Officers' Association on behalf of the Regular Forces Resettlement Service, the course provides two years' training for between 110 and 180 officers over the next four to five years.

COURSES

Control and Instrumentation of Reactors.—Harwell reactor school will hold a course on this subject from October 6 to 11 this year. Fee: 25 guineas, exclusive of accommodation. Application forms and further details from the Principal, Reactor School, A.E.R.E., Harwell.

Nuclear Reactor Technology.—A six weeks' full-time course is to be held at the Bradford Institute of Technology from June 2 to July 11. Fee: £30. Application forms and further information obtainable from the Principal, Bradford Institute of Technology, Bradford, 7.

FILM

A Measure of Maxam.—First of a series to be produced by the Maxam Division (Climax Rock Drill and Engineering Works, Ltd.) of the Holman Group on the applications of pneumatic methods to industry. Commencing with the manufacture of cylinders and valves and the operation of demonstration equipment, the film includes a number of industrial applications ranging from automatic clamping of components for machining to automatic dispensation of some 36 different specifications for stone chip mixtures at a quarry and a fully automatic conveyor system for mass production of car thermostats. In colour.

Processes and Equipment

Versatile Steam Raisers

Electrode steam boilers for three of the C.E.G.B. nuclear power stations have now been ordered from Bastian and Allen. Berkeley is to have a 4,000-kW unit operating at 11 kV, Hunterston will have two boilers, one of 1,750 kW and the other of 70 kW whilst Bradwell will have a 360-kW unit installed.

Electrode boilers have many advantages whether they are used for main steam requirements, for process steam or as standby plant. The equipment is fully automatic and the boiler can be arranged to start up with time-switch control at any hour of the day or night or by means of a pressure switch to maintain pressure or heat due to failure of other equipment.

A large electrode steam boiler may be used as standby plant for CO_2 generation and for initial generation on starting up. The same boiler or a small auxiliary boiler can be connected to operate from pressure switches to cut in automatically at any time for the liberation of small quantities of CO_2 to make up any leaks or losses. With a leak, the CO_2 pressure drops: this causes a pressure switch to close and energize the motor starter of the boiler feed pump. Steam is then available within five minutes. A boiler of this type can stand idle for long periods, even months, and still be relied upon to generate steam in five minutes from any given demand.

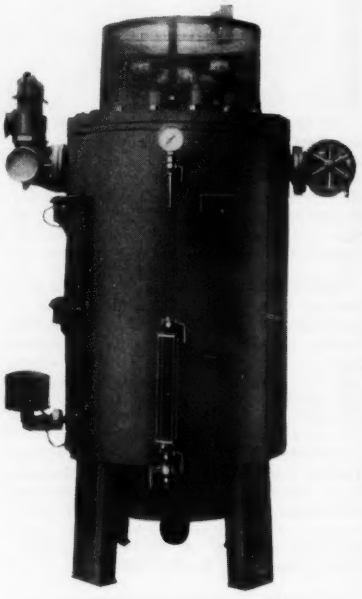
The electrode boiler is equipped with a load-setting switch which is adjustable from 10% to 110% of the rated value. The pressure modulator will vary the load automatically to reduce the load on rise of pressure or vice versa. A boiler with a loading of 1,200 kW, for instance, can be used with vaporizers to evaporate 4 tons of CO_2 per hour. As the maximum duty is only occasionally required, the load-setting switch can be adjusted as necessary; normally only about 20% of full load will be needed.

The electrode boiler takes up very little space; a boiler capable of generating 5,000 lb. of steam per hour is only 8 ft high by 3 ft diameter. No chimney or fuel store is necessary. The equipment is 100% reliable.

An important aspect of electrode boiler operation is the built-in safety feature: the water is the resistor and the electrodes are suspended from a top cover inside the boiler shell. The boiler is, therefore, absolutely safe when dry as no current can pass through and there are no elements to burn out. There is no limitation to the controls which can be incorporated to give the most flexible arrangement in providing accurate load, pressure or temperature control to meet any given set of circumstances.

(Bastian and Allen, Ferndale Terrace, Harrow, Middx.)

1117



Bastian electrode steam boiler with a maximum rating of 1,850 kW on a 660 V, 3-phase, 50 cycle supply. A unit similar to that shown here is to be installed at Hunterston.

Servo-driven Position Indicator

The new panel-mounted position indicator introduced by Sperry Gyroscope is especially suitable for recording the position of control rods. It has three types of presentation. Fine indication is provided by a clear-reading centrally-positioned digital counter. Five-digit presentation is standard, but smaller maximum counts can be arranged.

In order that the proportionate position of the transmitter can be seen instantaneously and without the need for interpretation a proportionate band indicator is included, consisting of a variable-length orange arc framed in the black background of the dial. This presentation is particularly valuable when the full-scale reading is less than 99999 on the counter.

The slow-motion tell-tale consists of a disc rotating behind a window in the lower part of the dial. It indicates movements whose rates are too slow to be immediately noticeable on the counter. Lines engraved on the disc can be arranged to give the correct sense of up and down or left and right movement if desired.

The three presentations, together with the synchro receiver, are geared together and driven by a two-phase servomotor. An error signal, caused by misalignments between the transmitter and receiving synchro, is amplified in the transistor amplifier incorporated in the indicator and energizes the servomotor, which drives the indicator until alignment is obtained. A velocity-stabilizing term to prevent hunting is obtained from a tachogenerator built into the servomotor.

The cylindrical case is arranged for panel mounting with connections at the rear by two Plessey 6-way plugs and sockets. The zero-setting control is also at the rear and therefore cannot be tampered with once the instrument is mounted.

For reactor control-rod position indication an ancillary feature is added. Under emergency shut-down conditions only, the indicator is unable to respond sufficiently rapidly to prevent the position error between the synchro transmitter and receiver from possibly exceeding 180°. In this event the motor will drive the indicator in the wrong sense in the shortest way to the final null position, and as a result a meaningless value will be indicated on the counter (twice full-scale reading instead of zero). A run-down button is therefore provided, which, when pressed, causes the instrument to be driven until the correct indication is obtained.

(Sperry Gyroscope Co. Ltd., Great West Road, Brentford, Middx.)

1118

Sperry control rod position indicator.

Wide-band Oscilloscope

A new wide-band general purpose oscilloscope designed to meet the full specifications of the North American and other world markets has been developed by E.M.I. Electronics. The Y amplifier bandwidth extends from DC to 50 Mc/s (−3 db), when a plug-in wide-band amplifier having a vertical sensitivity of 100 mV per cm is used. An alternative dual-channel beam switch plug-in unit gives a bandwidth of DC to 25 Mc/s, with a vertical sensitivity of 50 mV per cm. Details of other plug-in units, which are an important feature of the equipment, will be available shortly. These include differential input and high-gain wide bandwidth units.

Among the many new facilities incorporated in the WM7 is a push-button controlled cathode ray tube beam locating system which operates so that if the spot is deflected off the screen depression of the push-button confines the beam within a limited area on the screen, so that the normal shift controls can be used to centralize the display.

The instrument also employs a unique cathode ray tube display feature whereby parallax errors are automatically eliminated by a specially illuminated reflecting filter and graticule. A new type of 5 in. high sensitivity cathode ray tube has an accelerating potential of 10 kV. Two time bases are built into the unit, giving normal and delaying sweeps. The normal sweep speed is continuously variable over a range from 12.5 mu/s to 0.5 sec per cm.

(E.M.I. Electronics, Ltd., Hayes, Middx.)

1119

Crystals for Gamma-ray Counting

Thallium-activated sodium iodide crystals for various gamma-ray counting and spectrometry applications are now available from Ekco Electronics. In conjunction with a photo-multiplier tube, they can be used to form a scintillation counter of high counting efficiency. Among the features of these Ekco crystals is their high stopping power—the atomic number of iodine being 53, while their light output from gamma rays is twice that of anthracene.

Closely matching the spectral emission of available photo-multiplier tubes, Ekco crystals have a maximum response at about 4,100 Angstrom units and an approximate response time of one microsecond. Consistently high quality is maintained, the large, single crystals of sodium iodide containing thallous iodide being grown from a melt under closely controlled conditions. A careful check is made on the specially purified raw material to ensure that the lowest possible level of K^{40} contamination is maintained.

Where required Ekco crystals can be made with an extra high degree of resolution as a result of a new technique, consisting of treatment of the crystals after they have been cut from the boule. As an example, crystals 1 in. by 1 in. have been supplied giving peak to valley ratios on Cobalt 60 of five to one and better.

On all except the smaller crystals, a reflecting medium is packed around the crystal to increase the light output. High-viscosity silicone oil is used to form the optical joint between the crystal and the glass window of the cylindrical metal container. To protect the crystals, containers are hermetically sealed, but the crystals can be supplied without containers to special order.

Sizes of Ekco crystals range from 1¼ in. diameter by 2 in. deep to ½ in. diameter by ½ in. deep, the larger sizes being available with wells if required.

(Ekco Electronics, Ltd., Southend-on-Sea, Essex.)

1120

Quick Response Recorder

The new Evershed quick-response recorder is a continuous roll chart instrument incorporating two quick-response movements and recording electrically on teledeltos paper. The movement zero may be set in any position, and a marker pen is incorporated. Internal illumination is provided. The CRD 5 has chart speeds of ½, 1, 3 and 6 in. per sec, and CRD 6 speeds of 2, 4, 12 and 24 in. per min.

The recorder measures 13 in. by 11 in. by 6 in. and weighs 35 lb. and the separate amplifier unit 13 in. by 8 in. by 6 in. (approx.) weighs 26 lb. The amplifier unit comprises a power pack and two amplifiers, and an 18-core connector 5 ft long is provided. Power requirements are 115/230 volts 50/60 cycles a.c. (140 watts) and 15-20 V d.c. (3 watts) for the marker pen. Records can be taken up to 25 c/s with an amplitude error not exceeding 10% for a peak to peak deflection of 1½ in. At smaller amplitudes the frequency response is proportionally higher.

The sensitivity, ± 5 V for full-scale deflection of ± 1½ in., can be adjusted down to zero by potentiometer control. With this control in circuit the input impedance is approx. 50,000 ohm, and 2 megohms with the control switched out.

(Evershed and Vignoles, Ltd., Acton Lane Works, Chiswick, London, W.4.)

1121

The Mk. 1B Ultrasonoscope is playing an increasingly important part in the non-destructive testing of nuclear metals and materials. Recent applications include the ultrasonic examination of graphite, lead shielding blocks, heavy welds in pressure vessels and heavy plate for lamination. (Ultrasonoscope Co. (London), Ltd., Sudbourne Road, Brixton Hill, London, S.W.2.)

1122

Rotary Vacuum Pump

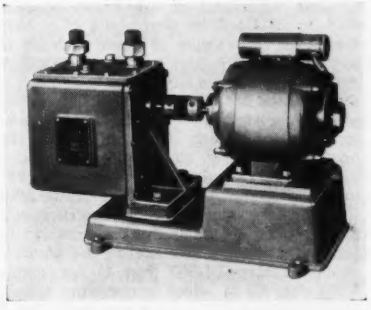
Latest addition to the Metrovac range of rotary vacuum pumps is the type DR210 comprising two single-stage, vane-type pumps mounted in a single oil tank and driven by a common shaft. The equipment, therefore, has the pumping characteristics of two single-stage pumps with considerable saving in space.

The pump is in good dynamic balance, the centre lines of the sliding vanes in the two rotors being arranged mutually at right angles: vibration is, therefore, greatly reduced. Operational noise has been kept to a minimum by the use of a quiet type of exhaust valve assembly and helical reduction gears

Like other small rotary pumps in the Metrovac series, the DR210 has an oil baffle, a sight glass, gravity drain plug and a pressure drain connection on the top cover. For situations where a gravity draining of the pump case is impracticable, a special pressure drain attachment can be supplied. The displacement of the DR210 is 1 litre/sec at 370 r.p.m. rotor speed for each section.

(Metropolitan-Vickers Electrical Co., Ltd., Trafford Park, Manchester, 17.)

1123



Metrovac DR210 rotary vacuum pump.

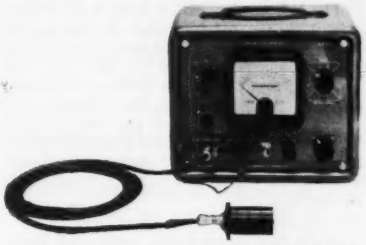
Radiation Measurement

Electronic Instrument's 37A portable electrometer is designed to meet a Ministry of Health requirement for a portable X-ray dosemeter. The instrument consists of a direct-reading, battery operated valve electrometer complete with ion chamber polarizing supply and a range of input capacitors and resistors in an attractive steel case.

All the high insulation input-circuit components, including the electrometer valve, are mounted in a lead-lined screening box. The case is sealed and desiccated to prevent damp from ruining the insulators. Dose ranges of 0.45 mr to 150 mr are obtainable.

(Electronic Instruments, Ltd., Lower Mortlake Road, Richmond, Surrey.)

1125



Electrometer designed to a M.o.H. specification for a portable X-ray dosemeter.

Metal Spraying

A new metal spraying gun, equally suited for use as an individual unit, or as an integral part of a large production set-up, has been introduced by Metallizing Equipment Co. The new unit, known as the Metco K metallizing machine, meets the current trend toward high-speed, semi-automatic, production metal spraying.

The gas-head employs the same basic principles as existing Metco metallizing equipment. The metal to be sprayed is in wire form, and is passed through a nozzle where it is heated by an oxygen-gas flame. A blast of compressed air surrounding the wire nozzle, atomizes and deposits the metal onto a prepared surface. The resultant deposit ranges from .001 in. to ¼ in. or more, has the corrosion qualities of the metal sprayed and extreme wear resistance.

The wire feed of the type K is driven by a high capacity electric motor, monitored by an electronic speed control system permitting adjustment of wire speed through the entire usable range. The power supply unit maintains constant wire speed, and automatically compensates for all the usual variations in line voltage. It operates from a single phase supply of 110-250 volts a.c. The controls provide high-speed acceleration and dynamic braking for instantly starting or stopping the wire feed during use, which, together with the speed control, can be operated by a remote unit. The motor, gearbox and control unit are totally enclosed and sealed to prevent ingress of metallic dust. All rotating parts run on ball bearings and the gears are sealed in gear oil which is pumped to provide positive lubrication in all operating positions.

(Metallizing Equipment Co., Ltd., Chobham, Woking, Surrey.)

1124

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 785,350. Method of separating nickel and cobalt. To: Lonza Electric and Chemical Works, Ltd. (Switzerland).

A mixture of nickel and cobalt hydroxides, at least a proportion of which are in divalent form, is oxidised in an aqueous medium so as to form a mixture of trivalent nickel hydroxide and trivalent cobalt hydroxide. This resulting mixture is subjected to an extraction treatment with an aqueous chlorine-containing liquor in an amount sufficient to cause dissolution of substantially all the nickel hydroxide while leaving the trivalent cobalt undissolved.

B.P. 786,286. Ionisation counter tube. E. Cohen. To: General Electric Co., Ltd.

The development of a high local field at the cathode can be avoided by making the cathode from an intermediate portion or intermediate portions of at least one continuous length of wire (instead of using sheet metal tubes), so that there is no mechanical joint between any two parts of the wire. The wire forms a closely wound structure, the spacing between adjacent windings not being greater than the diameter of the wire.

B.P. 786,486. Nut and screw mechanisms. J. A. F. Glass. To: U.K. Atomic Energy Authority.

Because of their different and conflicting requirements the normal operating control and the emergency control of the movement of the control rods into and out of the reactor core has been left to separate mechanisms, e.g., a gear assembly for normal operation and a pneumatic drive for emergency control. However, with small reactor cores consisting largely of fissile fuel and coolant channels with a moderator the problem of accommodating normal operating and emergency control units in the limited space becomes acute. The new nut and screw mechanism serves the dual function of operating an emergency control. The assembly moves in contact with liquid metal used to cool the reactor. A shaft rotates a screw and drives a nut in either direction along the shaft through a magnetic clutch. By de-energizing the clutch magnet in cases of emergency, nut and screw are released and fall immediately under gravity.

B.P. 786,733. Producing films of uranium oxide. To: U.K. Atomic Energy Authority (U.S.A.).

The relative proportions of different isotopes present in a radioactive element may be determined by measuring the intensity of the radiation given off by the element, e.g., by counting the number of alpha particles emitted from a given weight of the material in a unit length of time and comparing this count with a standard sample. It has been found that the desired accuracy can be obtained by forming on a metal support (disc) an adherent film of a compound of the radioactive element (oxide of the element). A film of uranium oxide is produced on a polished metal surface (gold or a metal of the platinum-palladium group) by spraying on that surface, in atomized form, a solution of a uranium salt (uranyl chloride) in an organic solvent (amyl acetate) containing a binder. The coating is heated to convert the salt to U_3O_8.

B.P. 786,760. Production of volatile halides of elements. R. Lind. To: U.K. Atomic Energy Authority.

A volatile oxyhalide of an element is vaporized and the vapour, together with excess halogen, is passed through a mass of carbon, in the form of a porous plug heated above the volatization temperature of both the oxyhalide and the oxygen-free halogenated element. The carbon plug is preferably made of activated wood or nutshell charcoal. The horizontal reaction vessel may be made of silicon and be provided with an electrical tubular heater. The outlet is connected to a condenser.

B.P. 786,800. Method and apparatus for the manufacture of anhydrous uranium fluoride and the like. M. Rouzet, J. Sauteron, P. Kertes. To: Commissariat à l'Energie Atomique.

Continuous production, despite the tendency of the mass to swelling, and with perfect purity, is made possibly by contacting countercurrently uranium dioxide powder and hydrafluoric acid gas at 500-600 deg. C. The powdery material passes downwards through a vertical chamber over baffles which are connected to a vibrating device so as to permit easy flow in contact with the gas.

B.P. 786,883. Method of purifying uranium. To: U.K. Atomic Energy Authority (U.S.A.).

In some uses of uranium, concentrations of boron over 0.5 p.p.m. are definitely objectionable. Uranium of low boron impurity may be obtained by electrolysis of a bath composed of a halide of uranium fused in a mixture of chlorides held at such a temperature that the metallic uranium is deposited as a coarse powder on a cathode of, e.g., molybdenum. Higher bath temperatures than 900 deg. C would reduce the boron content but cause difficulties owing to excessive corrosion and liquefying of the uranium at the cathode. The removal of further amounts of boron may be effectively accomplished by burning the uranium to form an oxide and then heating the uranium oxide to above 1,000 deg. C (preferably 1,200 deg. C) at which temperature a substantial proportion of the boron impurities is volatized from the oxide. The purified oxide then may be converted to the nitrate and uranium metal produced electrolytically without further increase in the boron content.

B.P. 787,359. Lubricants. A. Blainey. To: U.K. Atomic Energy Authority.

The lubricating action of graphite is partly due to an adsorbed layer of water on each of the individual flakes of graphite in the agglomerate. At high temperature graphite loses its lubricating qualities due to desorption of the adsorbed water. When graphite (or a metallic powder such as copper, bronze, aluminium) is milled with finely divided P.T.F.E. in a proportion of 6 : 1 (4 : 1) all particles become smeared with P.T.F.E. and this lubricant can be used in high-temperature work.

B.P. 787,742. Processes for producing uranium trioxide. To: U.K. Atomic Energy Authority (U.S.A.).

Treatment of uranium tetraoxide slurries or suspensions with aqueous ammonium hydroxide gives a material which upon heating yields a uranium trioxide capable of rapid and complete reaction with carbon tetrachloride.

B.P. 787,778. Method of producing hafnium-free "crystal-bar" zirconium from a crude source of zirconium. To: Commonwealth Scientific and Industrial Research Organization (Australia).

In order to reduce the number of steps in the process of producing pure crystal bar metal, zirconium carbide is converted to the iodide, which is then purified and subsequently decomposed. Crude carbide is first formed by heating zircon sand with carbon. The conversion is then carried out by heating the carbide in a stream of iodide to form tetraiodide.

B.P. 787,971. Devices for discharging rods of fissionable material from nuclear reactors. To: Commissariat à l'Energie Atomique (France).

When letting fuel rods drop by gravity, means must be provided for absorbing the shock, so that they are not broken by their fall. Use of viscous material may soil the inside of the reactor; metallic cushioning may cause uncontrollable rebound. The difficulties are overcome by a number of guiding chutes running along the end face of the moderator block passing slightly below, and parallel to, an inclined row of the channel discharge ends. Further chutes associated with the reactor shield connect the lower ends with the exterior of the reactor.

B.P. 788,239. Beryllium alloys. J. Williams, J. W. S. Jones. To: U.K. Atomic Energy Authority.

Skeletons of compacted beryllium powder are sheathed in magnesium foils or submerged in molten magnesium, then heated in an inert atmosphere sufficient to cause complete diffusion of one metal into the other. The alloys contain from 1 to 25% magnesium, the remainder being beryllium.

B.P. 788,241. Production of zirconium tetrachloride. J. S. Broadley. To: U.K. Atomic Energy Authority.

The method is based on the discovery that the known complexes of zirconium tetrachloride with phosphorus oxychloride and phosphorus pentachloride are smoothly converted to the uncomplexed zirconium tetrachloride by bringing the vapour of the complex into contact with carbon at elevated temperature.

B.P. 788,245. Alloys of titanium or zirconium intended for drawing into wire. J. E. Hughes. To: Associated Electrical Industries, Ltd.

Titanium and zirconium can be more readily drawn when tungsten and/or molybdenum are alloyed with the titanium or zirconium in an amount from 0.1 to 0.5 (weight) %.